

AD A140111

# AFRRI

## TECHNICAL REPORT

### Fallout: Its characteristics and management

K. P. Ferlic

20030110008

DTIC  
ELECTE  
S APR 16 1984  
A

DEFENSE NUCLEAR AGENCY  
ARMED FORCES RADIOBIOLOGY RESEARCH INSTITUTE  
BETHESDA, MARYLAND 20814


APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

84 04 13 102

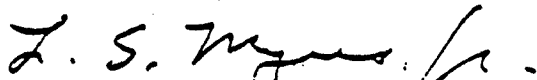
DTIC FILE COPY

AFRRI TR83-5

REVIEWED AND APPROVED



GARY H. ZEMAN  
CDE, MSC, USN  
Acting Chairman  
Radiation Sciences Department



LAWRENCE S. MYERS, Ph.D.  
Scientific Director



BOBBY R. ADCOCK  
COL, MSC, USA  
Director

Research was conducted according to the principles enunciated in the  
"Guide for the Care and Use of Laboratory Animals," prepared by the  
Institute of Laboratory Animal Resources, National Research Council.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFRRI-TR-83-5	2. GOVT ACCESSION NO. AD-A140 111	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FALLOUT: ITS CHARACTERISTICS AND MANAGEMENT		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) K. P. Ferlic		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Armed Forces Radiobiology Research Institute (AFRRI) Defense Nuclear Agency Bethesda, Maryland 20814		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NWED QAXM MJ 00001
11. CONTROLLING OFFICE NAME AND ADDRESS Director Defense Nuclear Agency (DNA) Washington, DC 20305		12. REPORT DATE December 1983
		13. NUMBER OF PAGES 100
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report is a comprehensive single-source summary of the salient features of fallout. It supplements the fallout lectures of the Medical Effects of Nuclear Weapons course given by AFRRI. The following topics are included: Basic physical processes that give rise to formation of fallout; identification of primary factors governing magnitude of the fallout problem; design and deployment of weapons and their effect on fallout formation; sources of fallout; weapon yield and atmospheric structure in region of detonation.		

DD FORM 1473

EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

including effects of local meteorological conditions on early fallout; theoretical and actual fallout patterns, with emphasis on the latter and on experience gained from atmospheric testing; expected type of fallout problem associated with a large-scale nuclear exchange; discussion of fallout deposition; identification of types of radiation associated with fallout, and discussion of their radiological properties; protection against each type of radiation; external hazards of fallout; major concerns of ingesting fallout; discussion of each major isotope of concern, with particular attention to current ICRP (International Commission on Radiation Protection) dose estimates for ingestion; brief description of management of fallout, including (a) detection of fallout and evaluation of hazards based on radiological dose considerations, fallout shelters, personnel decontamination, and food sources, and (b) postattack recovery. ↑

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

### ACKNOWLEDGMENTS

The author would like to acknowledge the following individuals who have assisted in developing the initial fallout lectures and the final publication of this report: Ray Gross for his enthusiastic support throughout the development of the fallout lectures, Mark Behme for his superb graphics, Jack Pitts and John Raymond for the numerous slides, Junith Van Deusen and Doris Pateros for their editorial assistance, and Betty Markovich and June Raney for preparing the text.

Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
Distribution/	
Availability Codes	
Avail and/or	
Dist	Special
A-1	



## **CONTENTS**

Introduction	3
Origins of Fallout	5
Design and Deployment of Weapons Related to Fallout	13
Yield and Atmospheric Structure	19
Fallout Patterns	27
Radiological Properties of Fallout	51
Internal Hazards From Fallout	67
Management of Fallout	79
References	99

## INTRODUCTION

Fallout is a phenomenon associated with a nuclear detonation. Much information is available about the properties of fallout and ways to protect against it. But experience has shown that many people have misinterpreted this information, and a broad grasp of authentic information on the subject of fallout seems to be lacking (1). This text supplies an overview of fallout by combining the salient facts from the references listed in the bibliography. In the discussion of fallout responses, the various policies recommended by the various military services are incorporated, when appropriate. This material will

1. Provide an understanding of what fallout is, where it comes from, and why it is a problem
2. Provide practical information to reduce the potential problem
3. Provide a brief, comprehensive, single source of information about fallout

## ORIGINS OF FALLOUT

### Initial and Residual Radiation

Ionizing radiation is produced whenever a nuclear detonation occurs. This radiation is arbitrarily divided into the initial radiation (that occurring within 1 minute of detonation) and residual (or delayed) radiation (that occurring after 1 minute\*). The initial radiation will consist of the prompt gamma and neutrons from fission, the very short-lived gammas produced from neutron inelastic scattering off air molecules, isomeric decay gammas, and gammas from neutron capture in nitrogen. The residual radiation will consist of radiation emitted from the weapons debris (i.e., fission fragments, unspent uranium or plutonium fuel, activated bomb components) and any neutron-induced material from the surrounding explosion environment.

### General Description of Fallout

The term "fallout" originated with the detonation of the first nuclear device. It was the TRINITY shot at Alamogordo, New Mexico, on July 16, 1946 (1). The term referred to the fact that the material "falling out" of the mushroom cloud produced by the explosion was radioactive. Present use of the term fallout refers to both a process and a phenomenon. The process is one in which the radioactively contaminated dust and debris (which have been airborne and transported by the radioactive cloud) fall back to earth. The term is also applied to the phenomenon to describe collectively the contaminated dust and debris that is or has been airborne.

Fallout is divided into two types: early and delayed. Early fallout is that returning to earth within the first 24 hours after detonation. The particles contain a high concentration of radioactivity, and vary from roughly 0.01 to 1 cm in size (or larger, close to the burst point) (2). Delayed fallout is that returning to earth after 24 hours, and is usually relatively low in radioactive concentrations. Particle sizes vary from a fine sand (approximately 0.01 cm) to a very fine sand (a few micrometers) (2). Delayed fallout is often subdivided into intermediate fallout, which returns to earth between 1 day and 1 month after detonation, and worldwide fallout, which returns to earth

---

\* The arbitrary time frame of 1 minute is based on the following conditions (2). The effective range of gamma rays from a 20-kt detonation is about 2 miles. The rise time to 2 miles for the cloud from a 20-kt yield is about 1 minute. Therefore, the gammas produced after 1 minute (i.e., 2 miles high) would have negligible effect at the earth's surface, and only the "delayed" or "residual" gammas would be significant when they return to the surface. Although the 1-minute unit was based on a 20-kt yield and although the effective range of the gammas from higher yields is larger, the rise time of the higher yield cloud is much faster. Therefore, the height of the cloud still approximates the range of the gammas. The reverse is true for yields of less than 20 kt. Consequently, the period of initial radiation (1 minute) is irrespective of the energy yield.



after 1 month. This division is based on the fact that suspended particle matter requires about 1 month to be distributed worldwide.

The most severe radiological hazard of early fallout is the external whole-body exposure to gamma radiation (1, 2). This exposure can vary from one that is negligible to one that is lethal. The second most severe hazard is external beta burns (1, 2). If properly handled, they are nonlethal (except for perhaps the most extreme cases). The third hazard is internal exposure from the ingestion of particles of radioactive fallout. The only real radiological concern from delayed fallout is from the ingestion of the longer lived radionuclides (2), such as strontium and cesium. All of the radiological hazards are discussed in later sections.

### Formation of Fallout

Whenever a nuclear device is detonated, a fireball is produced. The fireball is extremely hot ( $\sim 300,000^{\circ}\text{C}$ ), and all the atoms contained in the fireball (fuel, fission products, etc.) exist either in the gas or plasma state. Because of its heat, the fireball expands, engulfing and vaporizing the surrounding environment, and begins to rise at great speeds. As it rises, it creates a vacuum, which results in a tremendous updraft. As the surrounding atmosphere tries to fill the void created by the updraft, the afterwinds are produced. If the fireball is close enough to the ground, the strong updrafts result in the typical mushroom cloud (Figure 1). If the detonation is high enough, the updrafts may not disturb the ground, and no stem or chimney may be seen. Any structure or other material near the fireball will be either engulfed or sucked up in the updraft. If the

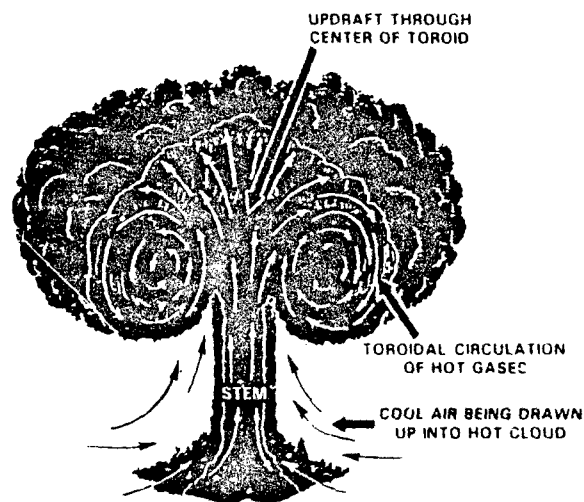


Figure 1. Cloud formation. Toroidal circulation within the radioactive cloud from a nuclear explosion.

fireball touches the ground, the heat will vaporize that part of the surface, forming a crater (Figure 2). The vaporized earth and ground will then be carried up into the cloud to whatever height the cloud ultimately obtains due to the upward movement of the updraft. The size of the crater depends on height of the detonation, energy yield of the weapon, and nature of the soil.

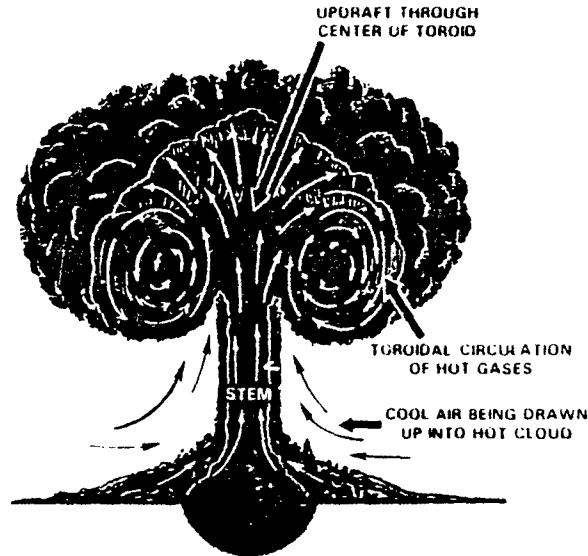


Figure 2. Crater formation. Toroidal circulation.

If the prompt neutrons released during the fission process strike the ground, then an induced area is produced (Figure 3). The induced area consists of activated ground material immediately adjacent to the burst point. Depending on height of the fireball and strength of the updrafts, the activated ground material may also be taken up into the mushroom cloud, which increases the total inventory of radioactive materials in the cloud.

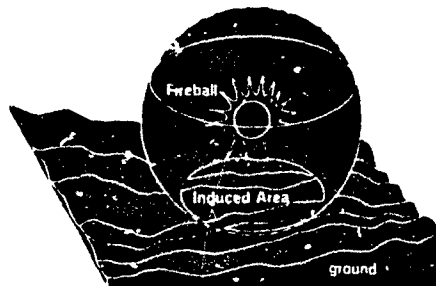


Figure 3. Formation of induced area

As the hot fireball and incorporated dirt and debris rise to higher altitudes, the vapors cool and condense to form a cloud containing solid particles. The cloud reaches its maximum height in about 10 minutes but continues to grow laterally, producing the mushroom shape (2). The fallout particles are produced during this cooling and condensation phase. The radioactive residue in the cloud condenses and fuses with the earth particles in the cloud. The radioactive contaminants are usually found in a thin shell near the surface of particles (2). In some particles, contamination has been found throughout the particle. This indicates that the materials were molten when the particles were formed (2). Particle sizes range from 1 cm to 0.002 cm (or less) (2).

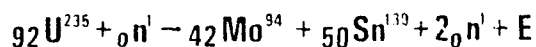
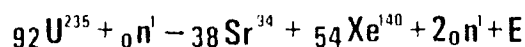
### Sources of Fallout Radioactivity

Some residual radiation will always be present in any nuclear detonation. In a standard fission weapon, residual radiation consists primarily of fission products, unspent fuel, and activated fission products. When describing fusion weapons, the terms "clean" and "dirty" are often used to compare their radioactivity relative to that produced in an equivalent "normal" fusion weapon (approximately 50% fission yield) (1). A normal fusion weapon is usually cleaner than a fission weapon of equivalent yield. A clean weapon is designed to yield less radioactivity than a normal fusion weapon. Only a small percentage of the total yield of a clean weapon comes from fissionable material (uranium or plutonium). The opposite is true of a dirty weapon.

The radioactive yield of a weapon can be intentionally increased through "salting," a process whereby a bomb is designed with certain elements that would substantially increase the radioactivity of the bomb debris produced on detonation.

In addition to the sources of radioactivity identified above (fission fragments, activated bomb materials, unspent fuel, and salting), induced ground elements may also enter the fallout cloud. Of these five sources of radioactivity, fission fragments are the greatest contributor to the fallout problem.

We may recall the fission process by examining two typical fission reactions:



Any one fission will result in two fission fragments of varying elemental form. For each kiloton of fission energy yield, roughly  $3 \times 10^{23}$  fission product atoms are formed, weighing about 2 ounces (2). On the average, the fission fragments will be approximately two fifths and three fifths of the original mass. The nucleus can split in about 40 different ways, thereby producing about 80 different fission fragments. The fission yield curve for uranium (Figure 4) gives the percent of fission yield plotted according to the mass number of the fission fragment. The observed fission yield ranges from as low as  $10^{-5}\%$  to a maximum of 6.4%. Most of the fission products fall into two broad groups; the lighter group varies mainly between atomic mass number of 80 and 110 with a peak at 95, and the heavier group varies between 125 and 155 with a peak at 139. For 1000 fissions of uranium, we can expect approximately 64 atoms of mass 95 and 139 (or about 6.4%) to be produced. Although the actual fission yield varies with both the fissioning nuclide (e.g., plutonium) and energy of the neutrons (e.g., 14 MeV), similar curves will be produced. As we shall see later, it is not surprising that the most significant long-term fallout hazards arise from cesium-137 and strontium-90, both of which have an atomic mass that falls near the fission yield peaks, and consequently they and their precursors have a high probability of production.

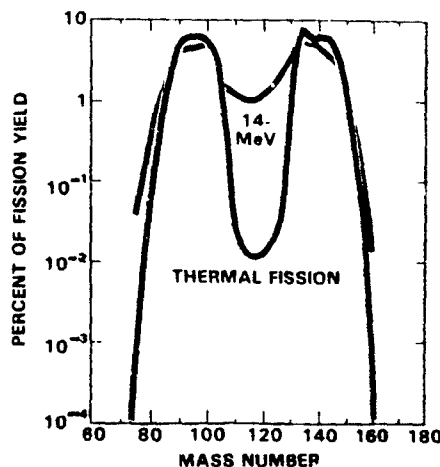


Figure 4. Fission yield curve for uranium

Most of the fission fragments are highly unstable and decay very quickly. Most (except for those few producing delayed neutrons) are beta emitters, and many will also produce gamma radiation. Each fission fragment frequently undergoes three or four decays before stability occurs. Although fission results in only about 80 different fission fragments due to the three or four beta decays, more than 300 different isotopes of 36 elements have been identified as being produced (2). Since each of these isotopes has a different half-life

and since the 36 elements all have different chemical properties (in particular, vaporization temperature), the resulting fallout problem is very complex. The actual fallout problem in a given area is determined greatly by how and when the various elements and isotopes return to earth. For example, the longer lived radioisotopes that last for many years become a long-term problem, whereas iodine-131 is an immediate problem because of its relatively short half-life (8 days).

In addition to fission fragments, unspent fissionable material is always present after a detonation. The fuel either does not react or it undergoes radiative capture (Figure 5) instead of fissioning. In radiative capture, the nucleus absorbs the neutron and emits a gamma ray. Both the unreacted fuel and the fuel that underwent radiative capture will decay by subsequent alpha and beta emission. Consequently, in addition to the beta and gamma radiation from fission fragments, the fallout field may also contain alpha radiation from either the plutonium or uranium fuels.

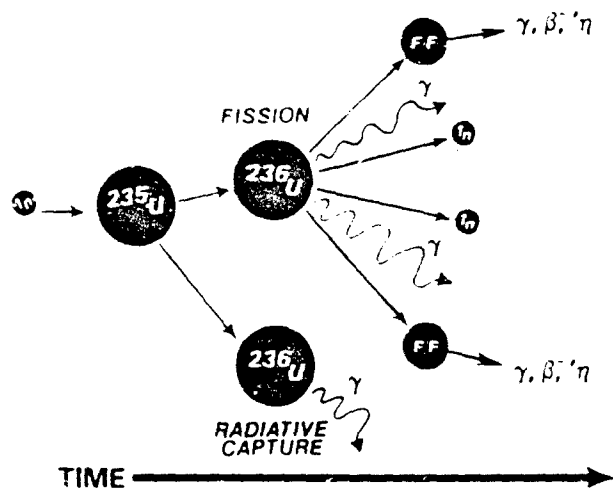


Figure 5. Possible outcomes of neutron capture in uranium

The induced radionuclides (such as activated bomb material, salting, and induced ground materials) also contribute to the radioactivity in the fallout cloud and are produced in a similar fashion. The materials are activated by the prompt neutrons through neutron capture (Figure 6).



Figure 6. Neutron capture

Neutron capture is essentially the same as radiative capture. In neutron capture, the target nucleus (e.g., bomb casing) captures a prompt neutron and forms an unstable compound state. The "compound" nucleus then decays by the emission of some particle(s) and returns to a stable state. Induced radionuclides from weapons normally decay through beta and are often accompanied by gamma emission. Alpha emission could occur if the original nucleus has an atomic mass greater than 208 (e.g., uranium-238 tamper or jacket). The actual induced radionuclides present are highly dependent on the characteristics of the weapon and the environment of the detonation. Table 1 (3) lists typical soil-induced elements on soils where nuclear detonations have occurred.

Table 1. Typical Induced Soil Elements

Soil Type	Minerals
I	Silicon, oxygen, trace
II	Sodium, potassium
III	Aluminum, iron, magnesium, titanium
IV	Silicon, oxygen

In general, the factors that will determine the absolute and relative radioactivity of the potential fallout problem are

1. total energy yield of the weapon
2. the fusion-to-fission fraction
3. design of the weapon
4. height of the burst
5. nature of the surface at ground zero

6. meteorological conditions

7. time after the explosion

Each of these items will be discussed in the following sections. It is of interest to note that because of the great variability possible in several of the above items (in particular, meteorological conditions), the energy yield of the weapon due to fallout is not figured into the energy yield of the weapon (2). Only the blast, thermal radiation, and initial radiation are considered. For a standard fission weapon, approximately 10% of the actual weapon yield is fallout. Therefore, a 90-kt fission weapon actually has a total energy output of about 100 kt. To put the fallout problem into perspective, up to 10% of a fission weapon's energy and its potential effect are left "up in the air" (literally and figuratively) after detonation. Fortunately, it does not all come down at the same time.

## **DESIGN AND DEPLOYMENT OF WEAPONS RELATED TO FALLOUT**

### Fallout from Past Detonations

A review of past detonations shows tremendous diversity in the problem of fallout. As previously stated, fallout was observed at TRINITY (19 kt). In the two subsequent detonations at Hiroshima (~12.5 kt) and Nagasaki (22 kt), weapons of similar yield were detonated, but one does not hear of a sizable fallout problem associated with these two detonations. A fallout of "black rain" and ash occurred over Hiroshima, but it was not radioactive, and so technically was not fallout. The ash was caused by fire associated with the detonation. The "black rain" resulted when rain removed a tremendous quantity of the ash from the air.

In the weapons test program, a few hundred square miles near the Nevada Test Site were contaminated with low levels of fallout. This was nothing compared to the fallout field of 7000 square miles produced at the Bikini BRAVO shot. The contamination was so extensive that survival or protection from radiation injury depended on evacuation or other protective measures (2). The field extended 350 miles downwind and 20 miles upwind; it was 60 miles wide at its maximum (2). Widespread fallout has also occurred whenever the Peoples' Republic of China performs its aboveground tests. At those times, south central Pennsylvania has detectable fallout. Such differences in fallout as observed above depend on the type of burst, yield, and meteorological conditions.

### Design of Weapons Related to Fallout

The explosive energy of any fission bomb is usually about 90% of the actual total yield. The remaining 10% is residual radiation, composed largely of fission products. In any fission process (Table 2), approximately 7% of the total energy released is in the form of the decay product of the fission fragments. (The neutrino energy 4%-5% is not considered, since neutrinos have a very small probability of depositing their energy in matter.)

The fission yield in any fusion device is only a fraction of the total weapon yield. The fallout usually depends on this fusion-to-fission ratio, and the concentration of the fission product is proportional to this fission-yield fraction. Although a fusion weapon does not have the quantities of fission products associated with a fission weapon of the same yield, its larger number of high-energy prompt neutrons contributes to residual radiation through activation of the surroundings of the explosion. In general, 95% of the energy from a normal fusion device is in the form of explosive energy, and only 5% is residual radiation. Therefore, in any detonation of a normal fusion device, the fallout problem is approximately one half as great as that of an equivalent yield fission device. Residual radiation of an enhanced radiation device is similar to that of a fusion device.



Table 2. Example of Distribution of Energy\* Among Fragments

Kinetic energy of fission fragments	82.5% $\pm$ 2.5%
Prompt gammas	03.5% $\pm$ 0.5%
Prompt neutrons	02.5% $\pm$ 0.25%
Delayed products:	
Betas	03.5% $\pm$ 0.5%
Gammas	03.0% $\pm$ 0.5%
Neutrinos	05.0% $\pm$ 0.0%

\*Released in a fission of uranium-235, with fission caused by a thermal neutron.

The total inventory of radioactivity due to weapons design depends on the fission fragments (as determined by the fission-yield fraction), activated bomb components, unspent fuel, and salting. The only other source of radioactive materials in fallout is the activated materials in the explosion environment. The quantities of these materials depends on the type of deployment of the weapon and the characteristics of the environment surface.

#### Airburst

An airburst is a detonation in which the fireball does not touch the ground. As a result, no vaporization of the ground surface occurs. The fallout problem depends on the height of the burst and the nature of the terrain, because strong updrafts could occur as the fireball rises. Depending on the strength of these updrafts and afterwinds, varying amounts of dirt and debris can be taken up into the cloud. The full effect on the subsequent fallout problem depends on two factors: (a) the amount of dirt and debris carried into the fireball, and (b) whether or not good mixing occurs when the fission fragments are still vaporized. Obviously, the closer the detonation is to the ground, the greater is its potential for hazardous early fallout. In general, fallout particles from an airburst (excluding a low airburst) are very small (0.1 to  $2 \times 10^{-5}$  meters) (2) since the cloud does not contain large quantities of dirt and debris. The small particles can go to very high altitudes and, in the absence of snow or rain, early fallout is generally not significant (2). These particles remain airborne for long periods of time, and decrease in overall activity through decay. The particles become widely distributed, which reduces their concentration. The primary radiological hazard from an airburst is the long-term delayed fallout. Also, a radiological hazard may occur in the vicinity of ground zero as a result of neutron activation of ground materials.

No early fallout occurred at Hiroshima and Nagasaki because both detonations were airbursts at 1670 ft and 1640 ft, respectively. These altitudes maximized the blast effects of the weapons.

#### Low Airburst and Near-Surface Burst

A low airburst and a near-surface burst are intermediate between the "ideal" airburst and the "ideal" surface burst. Although they may be strictly classified into one of the categories (e.g., the fireball in a low airburst would not touch the ground), other conditions may cause the fallout problem of one to resemble the fallout of the other. For example, a low airburst over the right surface with strong enough updrafts produces an unusual amount of early fallout because of good mixing between the fallout particles/vapors and the sucked-up dirt and debris. It would produce a fallout problem similar to that of a near-surface burst.

#### Surface Burst

A surface burst is a detonation in which the fireball touches the earth and causes the surface to vaporize. In addition, very strong afterwinds cause large amounts of dust, dirt, and surface debris to be sucked up into the fireball at a very early stage. A high degree of mixing occurs in the early stage of the fireball and cloud growth. As the fission products condense, they become fused with the foreign matter sucked up into the cloud. Highly radioactive, large particles ( $2 \times 10^{-5}$  m to 1 cm) are formed (2). Larger particles (greater than 1 cm), formed later with larger unvaporized or incompletely vaporized foreign material, return very quickly to earth near ground zero. The final composition of the cloud depends on the nature of the surface materials and the extent to which the fireball contacted the surface. The early fallout potential from a surface burst is extremely high (40%-70%) because of the large particles (2). A 60% early fallout fraction is normally assumed (2). The delayed fallout fraction that depends largely on conditions is a corresponding 30% to 60% of the total fallout problem.

It is of interest to note that a water surface burst results in almost the reverse fallout problem; i.e., early fallout is 20%-30%, and delayed fallout is 70%-80% (2). This reversal of the early fallout and delayed fallout is due to the size of particles. In water surface bursts, development of the fireball is the same as in bursts over land, except that sea salts and water are sucked into the cloud. Because the vaporization point of water is 212°F (100°C), the fallout particles form only after the cloud has cooled substantially, resulting in very small particles. These small particles remain airborne for long periods of time, thereby causing a problem of long-term fallout.

### Subsurface Burst and Deep Underground Burst

A true subsurface burst has no venting and so produces no surface contamination. In these cases the entire explosive energy yield results in shock and radiation, and any radioactivity formed is confined to the region near the point of detonation (except for some possibly escaping gases). On land, a subsidence crater may be formed, but it is not radioactive like the crater formed by a surface burst.

### Shallow Subsurface Burst and Underground Burst

A shallow, subsurface land burst is one in which the fireball does not emerge from the ground; it would probably be used for cratering. For example, this device could be buried in a narrow mountain pass at a depth that would maximize the size of the resulting crater in the mountain valley. This would prevent the opposing forces from advancing, retreating, or delaying their movement. Since contact with the earth is present early in the formation of the underground equivalent of the fireball, a high degree of mixing of materials occurs. High levels of contamination will be found in the crater and surrounding areas. Depending on meteorological conditions, the small particles may remain suspended for some time and descend at great distances from the burst point. As the depth of the detonation becomes shallower and the fireball is formed and emerges from the surface, the effects become increasingly like those of a true surface burst.

Another important type of shallow subsurface burst is a shallow-water, subsurface burst, which could occur near a port facility or invasion beachhead. Several important facts were learned during the BAKER shot (20 kt) at Bikini in 1946. (Bikini BAKER was a test designed to observe the effects of a nuclear detonation on surface ships anchored near Bikini Atoll.) Although the water was contaminated in the area surrounding the detonation, the attenuation capabilities of the ships would have offered sufficient protection to crew members to traverse the contaminated area while receiving only a small dose (2). (For extended discussion of attenuation of fallout and subsequent protection from fallout, see the section on protection from radiation fallout.) The only significant problem was the fallout, which consisted of both solid particles and a slurry of sea salt crystals in drops of water. This contamination was difficult to dislodge from the ships used in the test (2). If there had been any personnel on these ships, they would have been exposed to a considerable dose of radiation unless the fallout could have been removed immediately (2). As a result, the U.S. Navy instituted a water washdown of ships (2). This test and subsequent tests indicated that there is no simple system of predicting residual radiation for underwater bursts, as there is for land surface bursts (2).

### Bomb Craters and Ground Zero

Before considering how meteorological conditions affect fallout, it is appropriate to evaluate the effect of the crater and the induced area on military operations. The craters accompanied by a reasonable fallout problem will be those resulting from a surface burst (Figure 7) (2) or a near-surface burst (Figure 8) (2).

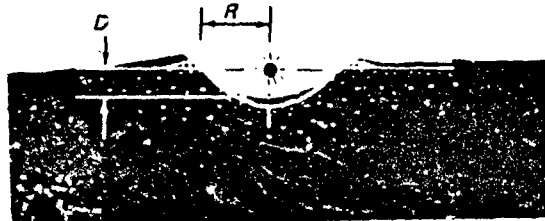


Figure 7. Surface-burst crater. R, radius of crater; D, depth of crater.

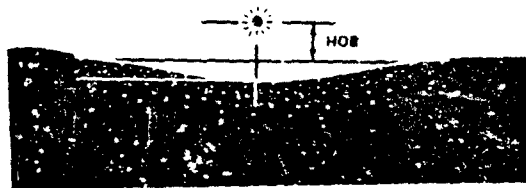


Figure 8. Near-surface-burst crater. HOB, height of burst.

Besides containing the largest fallout particles, these craters are part of the induced area from prompt neutrons. Since waste disposal will be a large problem in the postnuclear environment, it has been suggested that craters could function as a ready-made trash dump (4). Unfortunately, near the crater from a surface burst, radiation levels of about  $10^4$  R/hr at 1 hour are expected (4). Table 3 (3) gives some examples of the dose rates observed at ground zero from low airbursts. At the induced area, the activation will exist to a depth of about 0.5 meter, with most of the activation in the top 10 cm of soil, in contrast to the dustlike fallout on the surface (5).

Table 3. Induced Gamma Radiation at Ground Zero for 10-Kt Low Airbursts

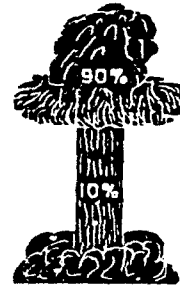
Soil Type	Ground Zero Dose Rates (rad/hr)	Radius 2 Rad/Hr (m)	Minerals
I	250	600	Silicon, oxygen, trace
II	2,900	900	Sodium, potassium
III	34,000	1,350	Aluminum, iron, magnesium, titanium
IV	30	250	Silicon, oxygen

The impact of the crater and the induced area is that no mission for military operations is likely to exist in the area for some time after detonation. If a crater should exist, it would be of relatively small size, and unless placed in a strategic location, it would be relatively easy to bypass.

## YIELD AND ATMOSPHERIC STRUCTURE

After considering the formation of fallout particles and their insertion into the atmosphere, we need to evaluate the conditions that control the return of these particles to earth. In general, the controlling factors are the type of particles formed, the yield of the original weapon, and the atmospheric conditions in the region of detonation. In any detonation that produces a mushroom cloud, about 90% of the contaminants are in the upper portion or head of the cloud, and the remaining 10% are in the stem (Figure 9) (6). The

Figure 9. Distribution of fallout in mushroom cloud



particles in the cloud will fall because of gravity. Their rate of fall depends on their aerodynamic characteristics (size, weight, shape, etc.) and on the particular characteristics of the air they are in. As stated previously, particles ranging in size from 0.01 cm to 1 cm in diameter normally arrive within 1 day, after traveling up to a few hundred miles (2). Delayed fallout varies in size from very fine sand to fine sand (0.01 cm) (2). Very fine sandlike particles are reasonably stable aerodynamically, and their rate of descent is determined by the air structure where the detonation occurs. Larger particles have a more unpredictable rate of descent. Although fallout sometimes occurs when the cloud cannot be seen, it is the larger, more unpredictable visible particles that present the most serious radiological hazard. They range in size from that of fine sand (0.01 cm) to that of marbles (1 cm) (2). Figures 10-13 (6) present several factors that govern the deposit of larger particles and the subsequent fallout problem.

Figure 10 shows that the larger, heavier particles leave the fallout cloud early and deposit in a region closer to the burst point, if wind and height of the cloud are constant. In a near-surface burst producing many large particles, the particles deposit early, producing a highly concentrated radioactive fallout pattern. On the other hand, if an airburst occurs, the particles are smaller and tend to settle at larger distances, thereby diluting the radioactivity by spreading it over a larger area.

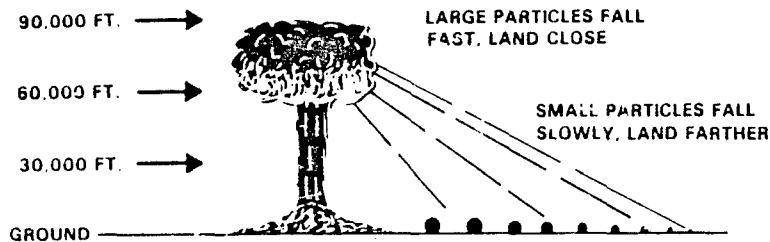


Figure 10. Effect of particle size on deposit of fallout, with constant wind and constant height of cloud

Differing wind strength (Figure 11) causes a similar result. Assuming that height and particle size are constant, a strong wind will cause the particles to travel greater distances. A stronger wind will spread the initial concentration over a larger area, thereby reducing its concentration and the subsequent radiological hazard.

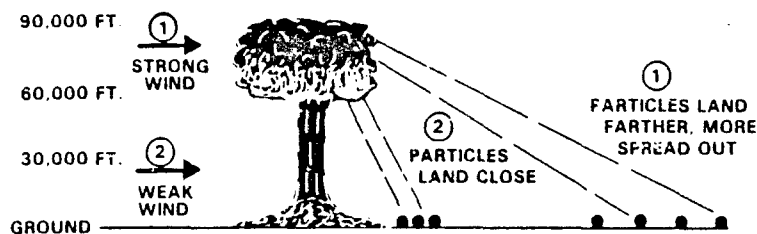


Figure 11. Effect of wind strength on deposit of fallout, with constant particle size

Figure 12 shows that, assuming wind speed and particle size are constant, the height of the cloud has a diluting effect on the concentrations of radioactivity in the fallout pattern. Since the higher particles take longer to fall, they can travel greater distances, covering more area and thereby diluting the radiological hazard in the fallout pattern. In addition, the longer the particles take to fall, the more they decay and also reduce the final radiological hazard in the fallout field.

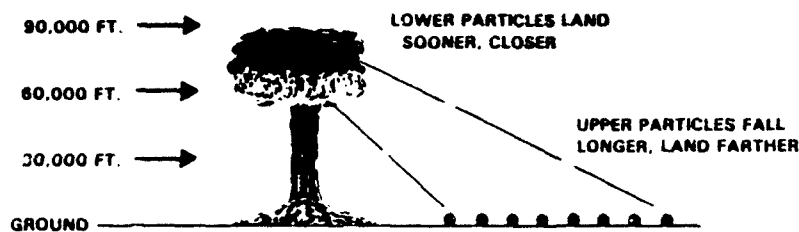


Figure 12. Effect of height of cloud on deposit of fallout, with constant wind and constant particle size

Figure 13 illustrates a complicating factor in predicting fallout. Assuming the same particle size and initial height, the variability of wind direction could completely reverse the expected fallout pattern. Since the speed and direction of winds vary with height in the atmosphere, the actual height of the cloud is a very important factor. A specific example of the problems arising from variations of wind is found in the discussion of the Bikini BRAVO shot and other actual fallout patterns later in this text.

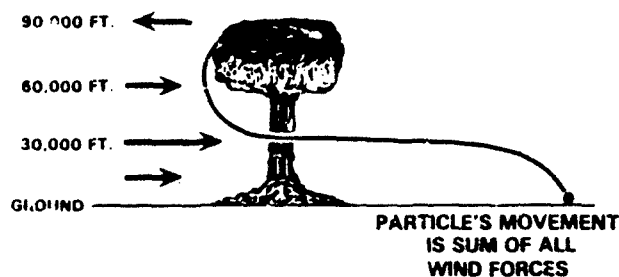


Figure 13. Effect of variable wind on deposit of fallout, with constant particle size and constant height of cloud

A brief discussion of the variability of winds across the United States is in order here. As described before and diagrammed in Figure 13, winds can cause fallout movement to vary greatly. In general, U.S. winds increase with altitude from the surface up to 30,000-40,000 ft. Above 30,000-40,000 ft, the winds decrease; at about 60,000-80,000 ft, they are relatively light. Therefore, the strongest winds at 40,000 ft would determine the general direction and length of a fallout area (2, 6).



In addition to the factors governing the rate of particle descent discussed above, another phenomenon that increases the particle-removing rate is scavenging. Scavenging is any process that increases the rate of removal of radioactivity from a fallout cloud. Actually, the process in which vaporized fission fragments condense on dirt and debris is a form of scavenging. But since it occurs at the time of particle formation, it is usually not considered scavenging. Precipitation scavenging is of main interest, and it can occur between 10,000 and 30,000 ft (2). Precipitation scavenging occurs in two forms: rainout and washout. In rainout (Figure 14), a rain cloud forms inside the radioactive fallout cloud. The rate of rainfall has

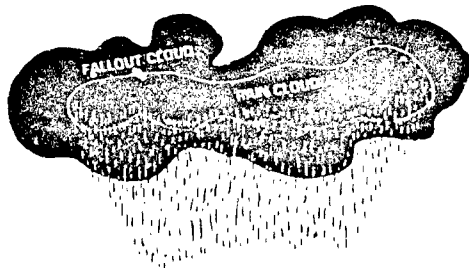


Figure 14. Rainout

little effect on the effectiveness of rainout. In washout (Figure 15), a radioactive fallout cloud passes below a rain cloud. The rain cloud thereby "washes" the fallout cloud. The strength of the rain and the length of time the radioactive cloud is washed markedly affect the percentage of cloud scavenged. Washout is greatly affected by the

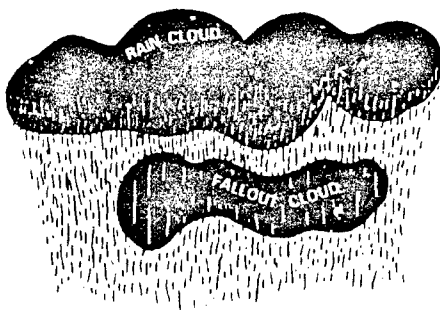


Figure 15. Washout

speed and direction of the rain cloud as well as when the rain cloud intercepts the fallout cloud. In general, evidence indicates that washout is far less efficient than rainout (2).

Precipitation scavenging of airborne fallout and the effect of rainfall on deposited fallout have several important consequences. From the standpoint of an overall fallout problem, any scavenging that occurs is beneficial because it decreases the radioactivity that could fall elsewhere. Unfortunately, scavenging causes a localized increase in the fallout rate, thus producing "hot spots" in the overall fallout pattern. In general, these spots are unpredictable; if they occur over populated areas, they add to the local radiological problem. Rain has a somewhat cleansing effect on deposited fallout on higher ground and elevated structures, but it causes increased concentrations of fallout in lower areas. Rain can also wash some of the fallout into the soil, which then acts as a radiation attenuator or absorber, thereby reducing some of the radiological problem.

As mentioned several times, the height of the cloud is very important. The actual cloud height obtained will depend on the heat energy of the weapon (or yield) and the atmospheric conditions. The most important atmospheric conditions are moisture content, stability, and local structure of the atmosphere. The three main regions of the atmosphere are the troposphere, tropopause, and stratosphere. The portions of the atmospheric structure with the greatest bearing on fallout are diagrammed in Figure 16.

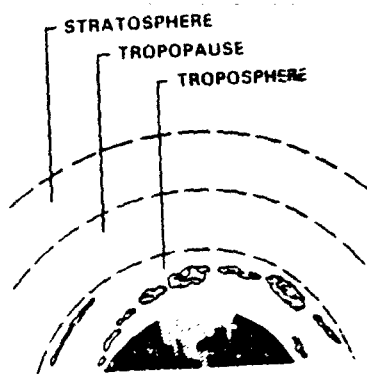


Figure 16. Structure of the earth's atmosphere

The visible phenomena associated with weather (i.e., clouds) occur in the troposphere. The tropopause is the top layer of the troposphere, separating it from the stratosphere. The stratosphere is exceptionally stable air whose altitude varies with the season and latitude. Figure 17 illustrates the change in altitude of the tropopause with latitude. As seen, the tropopause is much lower at the midlatitudes than in the tropics, and it will vary from about 55,000 ft at the equator to 25,000 ft at the poles (2, 6). It should be noted that most of the probable nuclear exchange targets are in the mid- or northern latitudes.

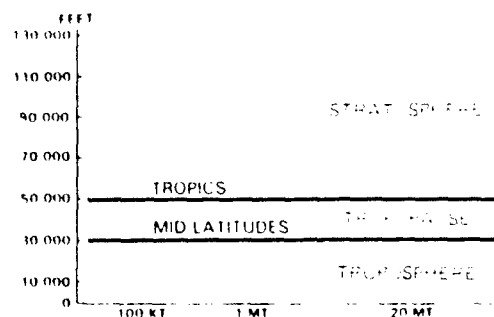


Figure 17. Variation in tropopause height relative to latitude of the earth

The maximum height of the cloud is strongly influenced by the tropopause. When the radioactive cloud reaches the tropopause, it tends to spread out. If sufficient heat energy remains, a portion of the cloud will penetrate the tropopause and enter the stratosphere. Figure 18 (6) compares three yields and their heights of cloud rise with varying latitudes.

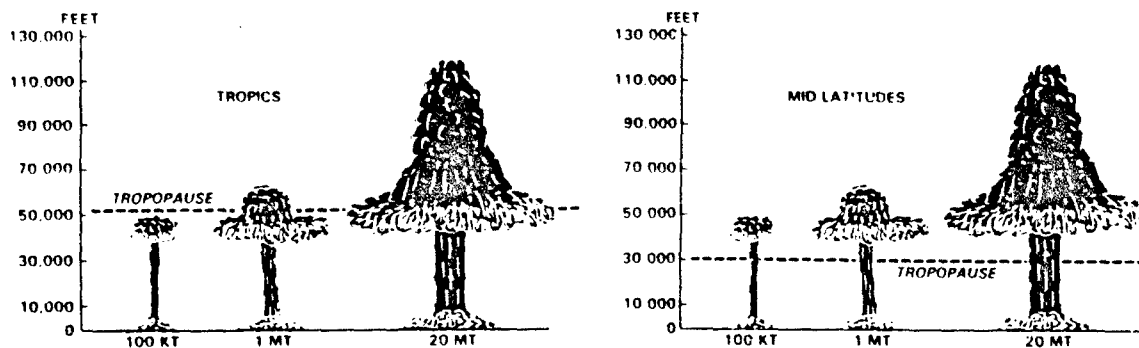


Figure 18. Yield and atmosphere structure

As seen, for an equivalent burst, more debris will tend to enter the stratosphere in the temperate and polar regions than in the tropics. This is because tropopause is lower in the temperate zones (as stated above) and the stratosphere is less stable in nontropic regions. For low-yield weapons, most of the radioactivity tends to stay in the troposphere. Obviously, large, aerodynamically unstable particles tend to fall at almost any height, but the fallout pattern of the very small particles depends on whether they stabilize in the tropopause or in the stratosphere. The region of stabilization of very small particles depends on the yield of the weapon, height of the burst, environment of detonation (for example, moisture content of the atmosphere), and height of the tropopause.

If the particles stabilize in the troposphere, they become part of the tropospheric fallout. Tropospheric fallout consists of very fine particles that are very slowly settled by gravity over several months. The fallout, spread by westerly winds, will be worldwide in about 1 month (2). The most important mechanism for deposit of tropospheric fallout appears to be the scavenging effect of precipitation (2). The removal rate is proportional to the amount that is present with a half residence time of approximately 30 days (2). The half residence time is the period of time required for the removal of one-half the suspended material at a given location.

Stratospheric fallout is characterized by very slow descent of particles. No scavenging takes place. By way of removal, the fallout particles move from the stratosphere into the troposphere, where they are scavenged. They may move from the stratosphere into the troposphere (2) by three methods: (a) direct downward movement of the particles, (b) upward movement of the troposphere, and (c) turbulent, large-scale, meandering, horizontal circulation through tropopause gaps. The relative importance of each depends on the altitude, latitude, and time of year. Since very little debris crosses the tropopause in equatorial regions, regardless of where the fallout was injected into the stratosphere, the stratospheric fallout will reach the earth in the temperate latitudes (2). The half residence time for transfer to the troposphere is about 10 months (2). The stratospheric fallout, upon entering the troposphere, will then be scavenged in the troposphere.

## FALLOUT PATTERNS

### Background

In the previous sections, the sources of fallout were identified, and the influence of the atmosphere on particle descent was discussed. In this section, the actual deposition of fallout and the associated levels of external radiological hazard will be presented. Before looking at fallout deposition, it is appropriate to quickly review a few items. A roentgen is a unit of radiation exposure; it refers to the amount of radiation present in the radiation field and its potential for depositing a dose. One roentgen is equal to  $2.083 \times 10^9$  ion pairs per gram of air at standard temperature and pressure. A rad is the unit of absorbed dose. It is equivalent to 100 ergs of energy deposited per gram of irradiated material. The rem is a unit of dose equivalent; it is a measure of the relative effectiveness of the absorbed energy in causing a biological effect. To determine the exposure of tissue to gamma radiation (the primary hazard from fallout), the following approximation is used:

For gamma tissue doses, 1 roentgen  $\approx$  1 rad = 1 rem

Henceforth, the above three units will be used interchangeably. To put the fallout pattern into perspective as a radiological hazard, the dose-prognosis table (Table 4) can be used.

Table 4. Dose and Resulting Prognosis

Dose (Rem)	Prognosis
0-100	Excellent (subclinical)
100-200	Excellent (clinical surveillance)
200-600	0-90% mortality (therapy effective)
600-1000	90%-100% mortality (therapy promising)
1000+	100% mortality (therapy palliative)

PRECEDING PAGE BLANK-NOT FILMED

### Prediction of Fallout

Although one may expect the prediction of fallout to be complicated, a first estimate can be made solely on the yield of the weapon. If we know the yield and type of weapon, we also know the fission product inventory. In fact, for a 1-kt detonation, at 1 minute after detonation there will be  $3 \times 10^{10}$  curies of radioactivity; after 1 day, it will decrease by a factor of 2000 (2). If this yield is spread uniformly over a smooth, infinite plane, a 1-kt yield per each square mile would produce 2,900 rads/hr at 1 hr at a height of 3 ft above the plane (2). Unfortunately, weapons testing data indicate that such a model is a gross oversimplification. The main problem is that a uniform plane is impossible, for several reasons: (a) Larger particles fall more rapidly and carry more activity, so more of the fission fragments (and overall activity) fall near ground zero. (b) The earth is not smooth. (c) Winds tend to dilute the radioactivity. (d) Scavenging is present. (e) Most importantly, fractionation causes depletion of some radionuclides.

Fractionation is a process whereby fission products attach to the solid particles in the fallout cloud in such a manner that the fallout near ground zero has radiological properties that differ from those of smaller particles that leave the cloud later. There are two causes of fractionation. The first is the change in state of the fission products. As the radioactive cloud cools, the more volatile elements condense at a later time onto the smaller particles. Consequently, the near fallout is devoid of the more volatile elements with lower condensation temperatures. The reverse is true for the less volatile elements. The second cause of fractionation is the change in elemental form of the fission products. For example, krypton and xenon, both inert gases, decay into rubidium and cesium, respectively. The fallout near ground zero is devoid of not only krypton and xenon but also their decay products, rubidium and cesium. On the other hand, the smaller particles, which have been in the fallout cloud for some time, will have condensed on them rubidium and cesium plus their decay products, strontium and barium.

It is of interest to note that a sea surface burst has less fractionation than a land surface burst. This is due to the fact that the radioactive cloud, which contains vast amounts of sucked-up water, must cool to 100°C before any particles begin to form. Actually, it is somewhat fortunate that the fallout process cannot produce the ideal plane as proposed above. In reality, greater contamination and higher dose rates occur closer to ground zero (where most of the destruction has occurred), and lower dose rates occur elsewhere.

Although the fallout model proposed above is an oversimplification, it does identify several important variables that must be known for prediction of fallout. To predict the magnitude of a fallout problem, one needs to know the total fission yield, the height of burst, and wind structure at the top of the cloud. The total fission yield will identify the quantity of fission products to be released. The height of

burst will identify both the possibility of induced activity and the expected (relative) particle size. The wind structure at the top of the cloud identifies the direction and speed of the cloud. In addition to the above information, the following is needed to predict the extent of the fallout problem: all meteorological information acting on the fallout cloud (i.e., changing wind direction, changing wind speed, any seasonal conditions), actual dimensions of the cloud, distribution of radioactivity in the cloud, actual range in size of particles formed, any potential scavenging (are any rain clouds on an intercept course?), and any potential fractionation. Unfortunately, several of these necessary variables will be unavailable until after a detonation. Consequently, the accuracy of any fallout prediction is limited by these variables.

The nuclear testing data are limited. [All yields on the Nevada Test Site are less than 100 kt, and none are true surface bursts. The detonations at Enewetak Proving Grounds (Enewetak and Bikini) are in the megaton range and are shallow-water surface bursts, and the fallout patterns are inferred from radiation measurements over water (2).] However, those data, in conjunction with natural phenomena (such as volcanoes), scientific experimentation, and calculations, have yielded much information on the magnitude and extent of the fallout problem and its radiological threat to personnel on the ground. Several methods of varying degrees of complexity have been developed for predicting dose rates and integrated (total) dose curves to persons on the ground at varying locations. Since we cannot know beforehand the factors causing deviations in fallout patterns, idealized fallout patterns are frequently used to provide an estimate of the contamination picture.

Although the ideal fallout patterns do not incorporate many of the irregularities that exist in a real fallout field, the patterns are very useful for planning purposes and for estimating the effects of nuclear attack. Of course, the patterns will overestimate or underestimate the radiation levels at a particular location; nevertheless, they will provide a good estimate of the gross fallout problem over the entire affected area.

#### Ideal Fallout Patterns

The ideal fallout pattern is based on a given weapon and yield. Then, using only the fission yield of the weapon, we determine an average fallout pattern for a given wind condition (no shear or change). In addition, the ideal fallout pattern assumes smooth, open terrain. The ideal fallout pattern will result in ideal isodose rate curves with a cigarlike shape, having an ideal width and an ideal distance upwind and downwind. The dose rates given in the ideal fallout pattern are external gamma dose rates. Figure 19 (2) is a typical ideal fallout pattern that might be obtained. The dose rates may or may not be normalized to a unit time (usually  $H + 1$  hour).

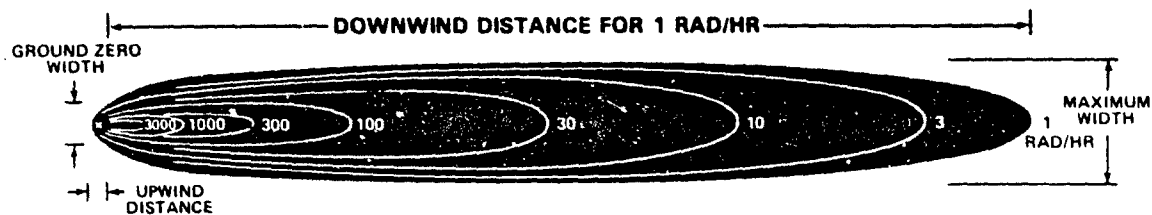


Figure 19. Pattern of idealized unit-time dose rate

Since fallout gradually descends over a period of time, it is beneficial to look at a time sequence with ideal fallout patterns. Figure 20 (2) shows the dose rate contours from early fallout at 1, 6, and 18 hours postdetonation for a 2-megaton surface burst with a 1-megaton fission yield and a 15 mile-per-hour effective wind speed. As seen, a person 20 miles downwind from the explosion would find himself in a 3-rad/hr fallout field at 1 hour. This person would find the dose rate continuing to increase, so that at 6 hours after the burst, the dose rate 20 miles downwind would be over 100 rad/hr for this person. The dose rate would reach a maximum, either before or after 6 hours. It is at this time that the fallout has stopped at his location. Before this time of maximum dose rate, the fallout was not complete; so as accumulation of fallout increased, so did the dose rate. It is after this time of maximum dose rate that decay (according to the natural decay of the fission products) will be observable and dose rates will decrease. At 18 hours the dose rates will have decayed to near 30 rad/hr at 20 miles directly downwind from the detonation.

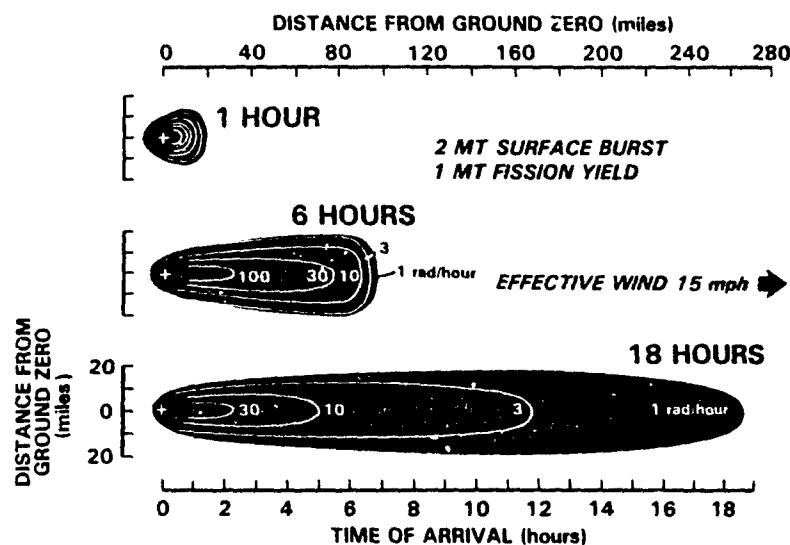


Figure 20. Contours of ideal dose rate versus time of deposit, for a 2-Mt surface burst and a 1-MT fission yield



In addition to the dose rates, one can use the ideal fallout pattern to assess the total dose delivered during the time of deposition (or infinite dose). Figure 21 (2) uses the same detonation and time frame, but the total doses delivered at 1, 6, and 18 hours are given. As seen in Figure 21, if our person at 20 miles directly downwind did not enter a fallout shelter, he would have received over 1000 rad at 18 hours. Referring again to Table 4, the prognosis for a person with a dose of over 1000 rads is not promising. Although it is understood that the ideal fallout pattern provides only average values, it does point out those regions in which fallout shelters should be seriously considered.

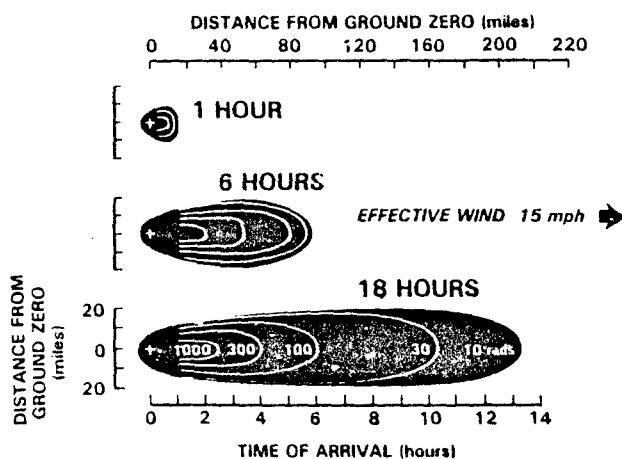


Figure 21. Ideal total dose versus time of deposit, for a 2-Mt surface burst and 1-Mt fission yield

Figure 22 is an overlay of the 18-hour dose-rate contours and the 18-hour total-dose contours (i.e., Figures 20 and 21 combined). Using this information and the dose estimates made according to the method described by Glasstone and Dolan (2), the total dose at 24 hours and 25 years can be made. Two points have been chosen: the intersection of the 30-rad and 3-rad/hr curves, and the intersection of the 10-rad and 1-rad/hr curve. In the first case, 30 rad would be received at 18 hours; if the dose rate does not increase after 18 hours, 75 rads would have been delivered 24 hours later ( $H + 42$ ) and a total dose of 210 rads in 25 years ( $H + 25$  yr). In the second case, 10 rad would have been received at 18 hours; again, if the dose rate does not increase after 18 hours, 25 rads would have been delivered at 24 hours later ( $H + 42$ ) and a total of 70 rads in 25 years ( $H + 25$  yr). Three important features about fallout can be learned from the example: (a) a large percentage of the total dose possible will be delivered in the first 24 hours, (b) after the first few days, dose rates will have decreased substantially, and (c) fallout shelters will be needed for only a relatively short time.

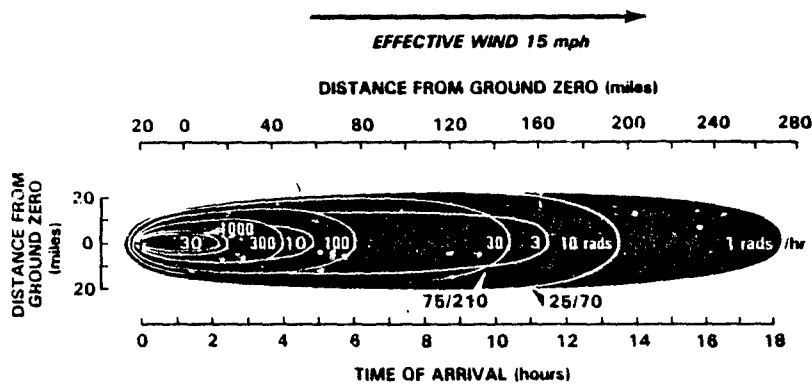


Figure 22. Total dose estimates at 24 hours and 25 years for a 2-Mt surface burst and 1-Mt fission yield

As was previously stated, the ideal fallout pattern fails to consider many variables. Figure 23 (2) is an expected ideal fallout pattern for a 10-Mt, 50%-fission surface burst with 30-mph winds. If local meteorological and surface conditions are included, the idealized pattern becomes that in Figure 24 (2). As seen, quite a few modifications occurred. In particular, the fallout pattern has changed directions and regions of localized hot spots have developed.

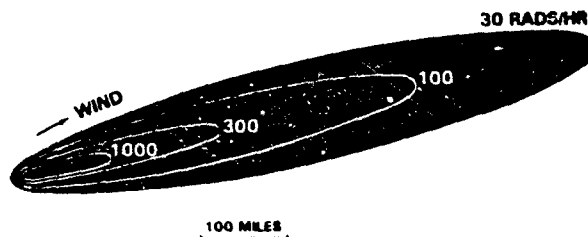


Figure 23. Ideal pattern for a 10-Mt surface burst and 50% fission, with 30-mph winds

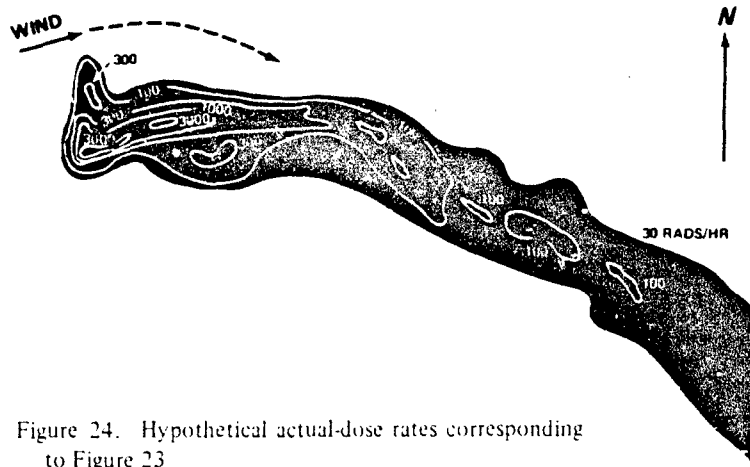


Figure 24. Hypothetical actual-dose rates corresponding to Figure 23

#### Actual Fallout Patterns

In comparing ideal patterns with actual patterns, a number of parameters may cause the real and ideal to disagree. Some disagreements will be caused by the original assumptions. For example, the ground roughness of a flat countryside can reduce the predictions of a smooth, flat plain by 70% (2). Similarly, ideal predictions are based on only the fission yield, whereas a real detonation will involve other activated materials. In general, the meteorological conditions will cause the most significant disagreement. The accuracy of prediction of fallout is very dependent on the quality of the available meteorological data (7). With precise meteorological data, we can make an excellent forecast of the area of fallout and the direction of the axis of the pattern can be made (7). It is obvious that the longer the time between the meteorological conditions used in a prediction and the actual event, the greater the uncertainties in the prediction. Weapons testing in the 1950's indicated that for times up to about 12 hours, the persistence of a prediction was as good as for a weather forecast, and that after about 2 or 3 days, a forecast is not much better than a climatological mean (8).

Since some populated areas off-site were affected by fallout from testing at the Nevada Test Site, it is appropriate to briefly discuss the (former) Atomic Energy Commission's off-site dose criteria for the protection of the public, before discussing actual fallout patterns. The basic requirement was that the whole-body gamma effective biological dose should not exceed 3.9 roentgen over a period of 1 year (9). This limit was for a single exposure or a series of exposures (9). (It should be noted that acceptable doses for both radiation workers and the general public in the mid-1950's were different from those considered acceptable today.) The effective biological dose should

not be confused with the absorbed dose or rad. The effective biological dose was an estimate of the biological damage dose, taking into account such factors as the length of time for delivery of a given dose (biological repair), the reduction of dose from shielding by buildings, and weathering (9). The effective biological dose is approximately one half of the infinite exposure (9). The infinite exposure is the exposure that results from the time of the arrival of the fallout until it has fully decayed. The infinite exposure assumes that the individual remains at the same location during the entire time. In addition to whole-body gamma measurements, the sampling of milk, water, and air was routinely performed (9).

Provisions were also made for unexpected high exposure rates and/or the need for localized decontamination (9). The off-site population exposure from nuclear tests at the Nevada Test Site has been recently (in 1981) reviewed (24). Approximately 188,000 persons received a collective exposure of 120,000 person-R between the years 1951 and 1970. [The collective exposure in person-R is the total sum of each individual's exposure in R (roentgens); i.e., two persons each with an exposure of 2 R result in a total collective exposure of 4 person-R]. The highest cumulative exposure at a population site during this time was 17.5 R (2-14 individuals), with the majority of the exposures (156,756) less than 0.5 R (24). The series of tests known as Upshot-knothole (in 1953), Teapot (in 1955), and Plumbbob (in 1957) account for the majority of the person-R (113,000) (24).

Figure 25 (2) is the early-fallout dose-rate contour from the BOLTZMANN shot at the Nevada Test Site. BOLTZMANN was a 12-kt, 500-ft tower shot on May 28, 1957. It is of particular interest because of the hot spot about 60 miles north-northwest of the Nevada Test Site boundary (2). Twelve hours after the shot, this area was found to be seven times more radioactive than its immediate surroundings. Total 25-year exposure (infinite exposure) was approximately 2.5-3.0 R in the region of hot spot. It was directly downwind of a mountain range, and rain was reported in the general vicinity at the time of the fallout (2). Either or both of these factors may have been responsible for the increased deposition of radioactivity.

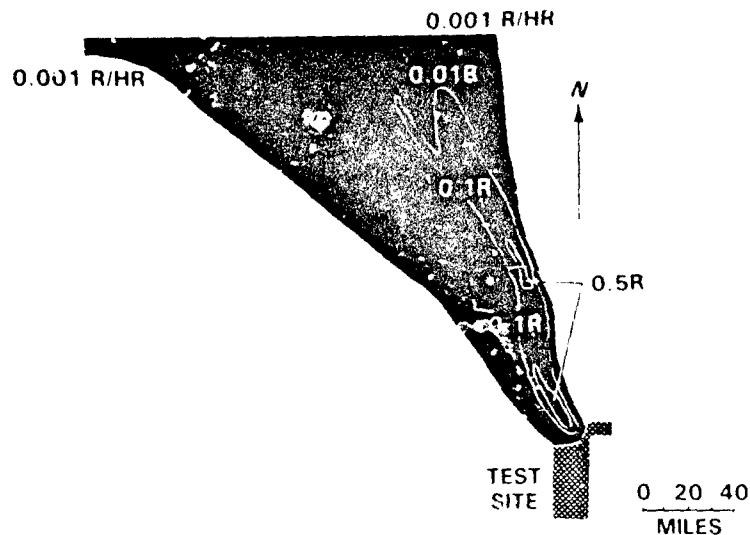


Figure 25. Early fallout from BOLTZMANN shot. Dose contour lines are for 12 hours postdetonation.

In operation Teapot at Nevada Test Site, 14 devices were detonated. Three devices were airbursts, so no fallout predictions were made. Of the remaining 11 detonations, 5 were in substantial agreement with predictions, whereas 6 deviated significantly from the predictions. Figures 26-30 (9) are five predicted and actual fallout patterns from these shots. Each shot depicts a particular aspect of the unpredictability that can exist at any detonation.

#### APPLE

APPLE (9) was a 14-kt, 500-ft tower detonation that was fired at 4:55 a.m. on March 29, 1955. The cloud was tracked at 21,000 and 13,000 feet. An additional sampling aircraft was also used. The maximum distance to which the cloud was tracked was 166 nautical miles on a bearing approximately 90 degrees. At the lower level, the bearing was between 60 and 70 degrees. Maximum cloud height was 31,000 ft. Fallout prediction was made at H - 1:30 (1.5 hr before detonation). Comparison of the prediction with the actual dose contours (see Figure 26) indicates that the predicted direction was off by 20 degrees and the 1-roentgen (R) infinite isodose contour extended only about one third of the predicted distance. Of particular interest from this shot are the variability of winds with altitude (although minor), the substantial concentrations of radiation near ground zero (isodose contours did not extend as far as predicted), and the localized hot spot near the city of Cedar City, Utah. The maximum effective infinite biological dose for a populated area outside the Nevada Test Site was 1.3 R.

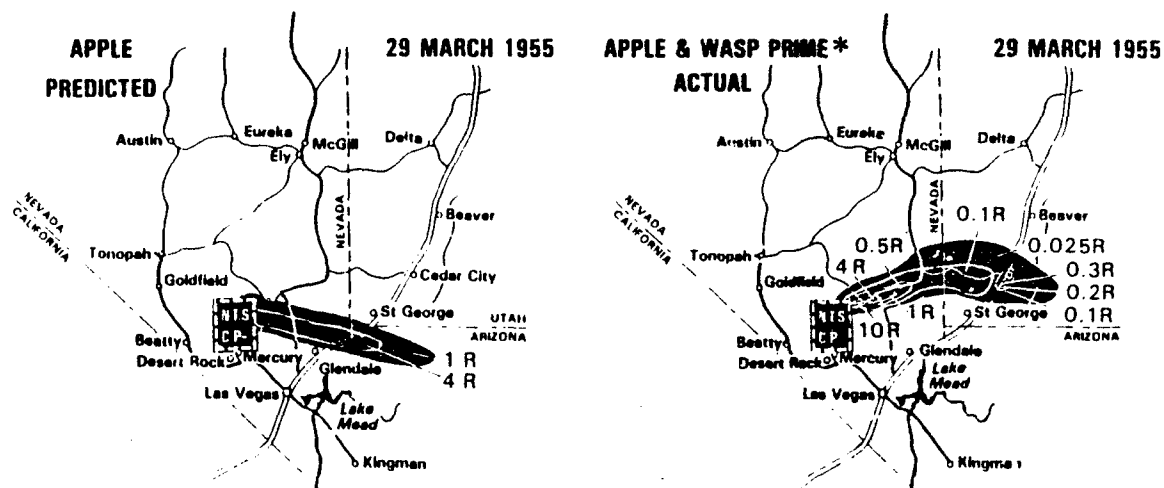


Figure 26. Predicted fallout and actual dose contours for APPLE shot. Actual dose contours are infinite dose contours. \*WASP Prime was a shot at 0455 the same morning. No separate survey was done since little fallout was expected due to type of shot.

## APPLE II

Figure 27 is the fallout pattern for APPLE II (9). APPLE II was a 29-kt, 500-ft tower detonation fired at 5:10 on May 5, 1955. The cloud was tracked at three levels (13,500 feet; 22,000-23,000 feet; and 28,000-30,000 feet), with additional sampling. Maximum cloud height was observed at 40,500 ft. Considerable shear was present, and the various tracked levels showed a spread in bearing from about 340 to 60 degrees. The cloud was tracked to a maximum distance of 120 nautical miles at all levels. The fallout prediction was made at H - 1:30. Comparison of the prediction and the actual pattern indicates good directional agreement but an overprediction in the length of isodose contours. One reason for the overprediction is the shear. The cloud was dispersed laterally to a great extent. As previously mentioned, the shear is very evident in the construction of the isodose lines on the actual fallout pattern. The maximum effective biological dose for a populated area outside the Nevada Test Site was 2.58 R. Of particular interest for this detonation is the effect of the wind shear. As seen, a fallout pattern can be substantially spread out, giving less activity per unit area than expected.

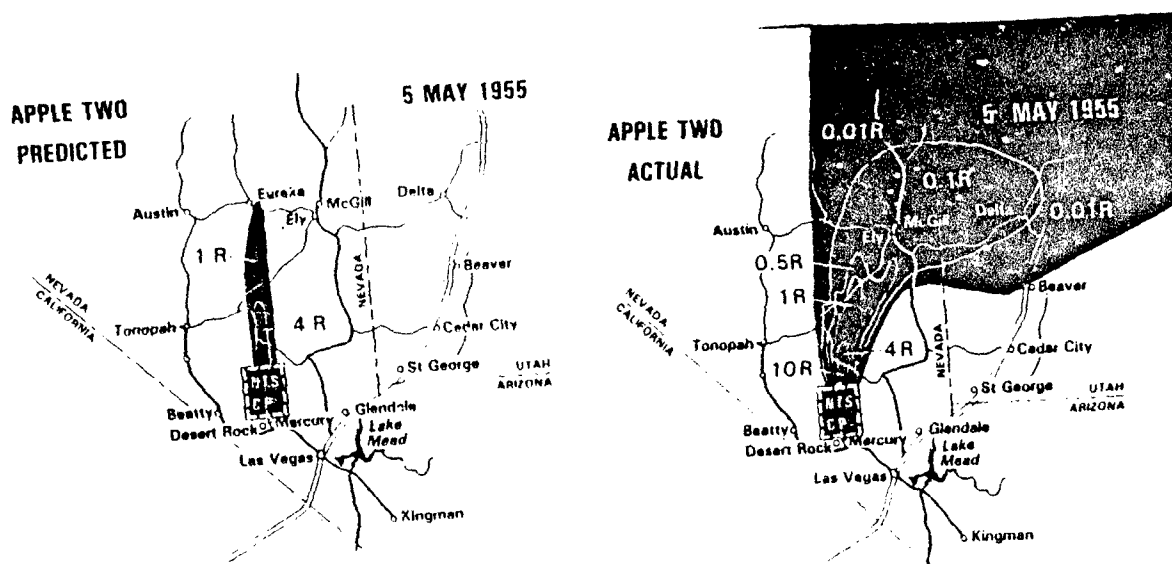


Figure 27. Predicted fallout and actual dose contours for APPLE II shot. Actual dose contours are infinite dose contours.

### ZUCCHINI

Figure 28 shows the fallout patterns for ZUCCHINI (9). ZUCCHINI was a 28-kt, 500-ft tower detonation that was fired at 5 a.m. on May 15, 1955. The cloud was tracked at three levels (13,000 feet; 23,000 feet; and 28,000 feet), with a sampler aircraft at approximately 35,000 ft. Maximum cloud height was reported to be 37,000 ft and stabilized at 36,000 ft. The cloud above 23,000 ft was tracked by all aircraft on an approximate bearing of 69 degrees for a distance of 213 nautical miles. The lower portion of the cloud was tracked for 145 nautical miles on a 118-degree bearing. A fallout prediction was made at H - 0:30. Comparison of the prediction with the actual pattern indicates an overprediction in the length of isodose contours and a 5-to 10-degree difference in direction. The maximum effective biological dose to a populated area outside the Nevada Test Site was 0.7 R. The most interesting aspects of this fallout pattern are, again, the variable winds with altitude, the overprediction of the isodose contours, and (very similar to the APPLE shot) a local hotter region near Cedar City, Utah.

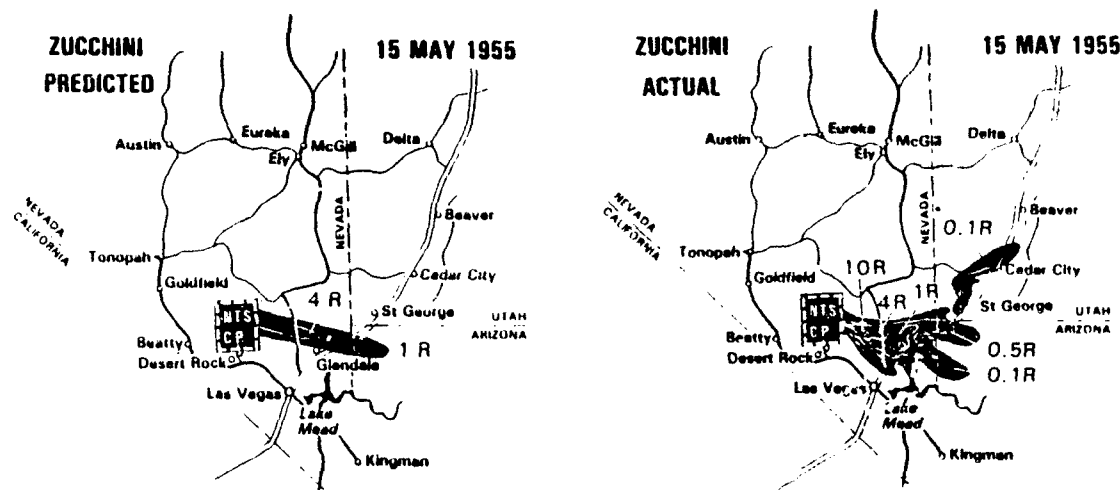


Figure 28. Predicted fallout and actual dose contours for ZUCCHINI shot. Actual dose contours are infinite dose contours.

### HORNET

Figure 29 is the fallout pattern for HORNET (9). HORNET was a 4-kt, 300-ft tower shot that was fired at 5:20 a.m. on March 12, 1955. The cloud was tracked at levels of 10,000-14,000 feet; 23,000-30,000 feet; and 36,000 feet. The maximum cloud height observed was 39,300 ft. The cloud was tracked to a distance of about 140 nautical miles, and then became so dispersed that any further tracking was impractical. The fallout prediction was made at H - 1:20. Comparison of the prediction with the actual pattern indicates good agreement in direction. However, the 4-R and 1-R actual isodose contours went to only a little over 50% of the predicted contour, and a reasonable shear occurred to the northeast. This fallout pattern does illustrate somewhat the uneven isodose contours that may be expected, particularly at relatively low doses. The maximum effective biological dose at a populated area off the Nevada Test Site was about 0.3 R. Several items are of interest on this pattern. Shear, as seen before, can cause quite unexpected changes in the predicted fallout pattern. In the case here, two separate fallout patterns were almost produced rather than one broad pattern, as in the other examples with shear. In addition, a low yield obviously will not have the fission product inventory to produce a large high-level fallout pattern. This reduced yield accounts for the quick dispersion of the fallout cloud relative to the other detonation already presented. In this detonation as before, the predicted isodose contours exceed the actual contours. Although the predicted isodose contours exceed the actual contours in all the examples presented here, it should be pointed out that this is not always the case. The actual isodose contours may equal or exceed the predicted, as in the MOTH and MET shots of the Teapot series (9). (The MOTH and MET shots are not presented here.) Modern methods of yield estimation make this less likely now than in the early days of testing.



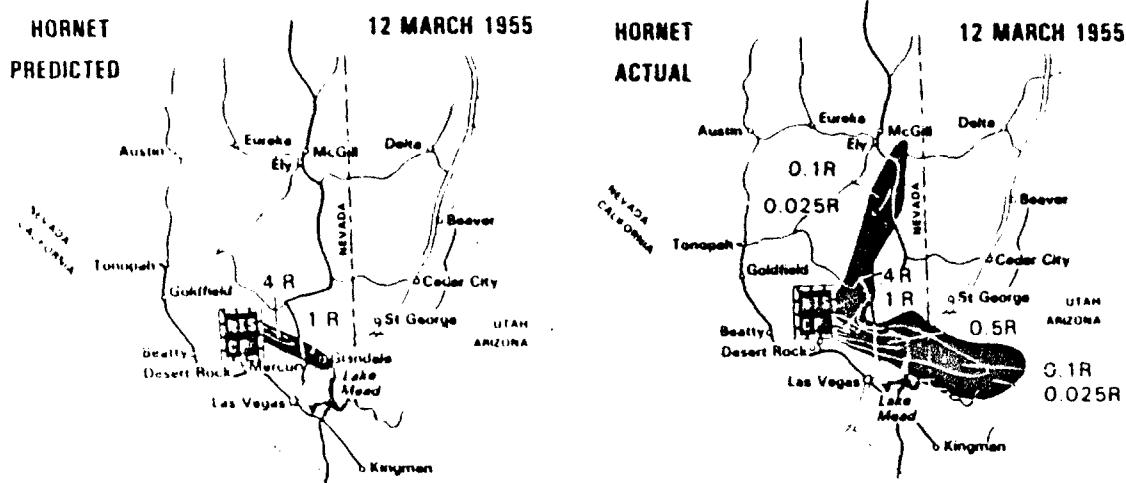


Figure 29. Predicted fallout and actual isodose contours for HORNET shot. Actual dose contours are infinite dose contours.

### TURK

Figure 30 is the unexpected fallout pattern of the TURK shot (9). TURK was a 43-kt, 500-foot tower detonation that was fired at 5:20 a.m. on March 27, 1955. Tracking was performed at four altitudes: 25,000-31,000 feet; 20,000-23,000 feet; 11,000-14,000 feet; and 36,000-42,000 feet. The maximum cloud height was observed at 42,000 feet. A fallout prediction was made at H - 8:00. Because of the wind pattern at shot time, the cloud became broken and dispersed in a very short time, with two general zones containing most of the cloud components. At altitudes up to about 28,000 ft, the cloud drifted generally into the northwest quadrant from ground zero, and the maximum distance was approximately 85 nautical miles at 20,000-23,000 ft, bearing 315 degrees true. The second zone was 40-105 degrees true at high altitudes above 30,000 ft; it extended to 105 nautical miles at 105 degrees true and to about 130 nautical miles at about 75 degrees true. In many instances, the cloud appeared to have several leading edges; at times, it doubled back on its previous path. Comparison of the prediction and the actual pattern indicates an extreme overprediction. This happened because a change in the frontal system caused a drastic reduction in wind speed, a rapid shift in wind directions, and thus a wide scattering of the fallout. In addition, the effects of the terrain on the fallout pattern were quite pronounced. The maximum effective biological dose at a populated area was about 0.16 R. The most interesting aspect of this fallout pattern is that no benefits are gained by having a prediction if the weather front changes. Thus, tactical moves are never made on the basis of a fallout prediction.

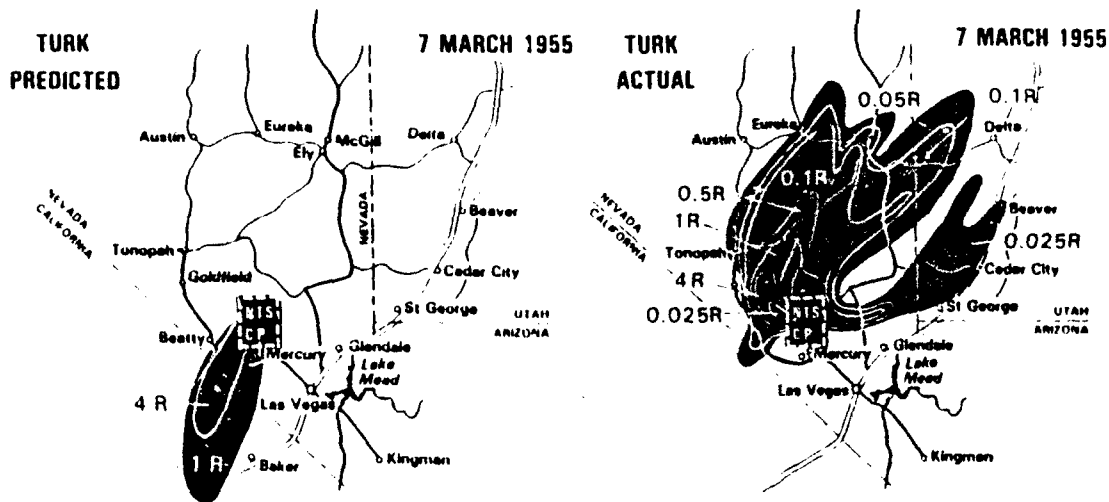


Figure 30. Predicted fallout and actual isodose contours for TURK shot.  
Actual dose contours are infinite dose contours.

#### Bikini BRAVO (Rongelap Incident)

Since megaton detonations could not be performed at the Nevada Test Site, such detonations were performed on various Pacific islands and atolls so that fallout could occur over uninhabited ocean. Bikini Atoll was an excellent location for such tests because the prevailing winds blew from the northeast to the southwest into open ocean. On March 1, 1954, the BRAVO shot was made during the CASTLE series. The BRAVO test was a thermonuclear device with an estimated yield of 10 Mt. The detonation was 7 feet above a coral reef. Upon detonation, the device exceeded the design specification and yielded 15-18 Mt. Since the design specifications were exceeded, the cloud went higher than expected; it was picked up by the jet stream and traveled due east. The subsequent fallout pattern consisted of radioactive particles 0.001 to 0.02 inch in size, contaminating an area 330 miles downwind, 20 miles upwind, and 60 miles east (2). An area of 7000 square miles was contaminated to such an extent that evacuation or protective measures were necessary to avoid death or serious radiation injury (2). Figure 31 (2) contains the maximum possible dose contours for 96 hours postdetonation.

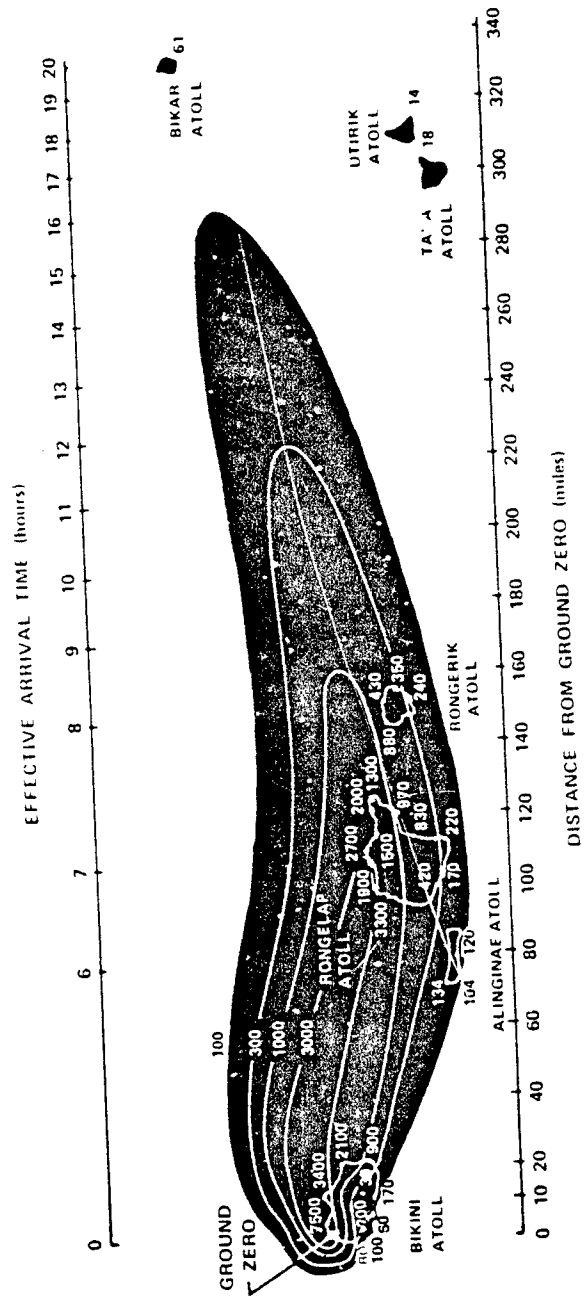


Figure 31. Fallout contours for the Bikini BRAVO shot. Dose contours are in rads for 96 hours postdetonation.

Since a major portion of the contours lies over water where no adequate measurements were made (2), the actual choice of fallout patterns does contain some guesswork. Although uncertainties exist in the 96-hour dose curves of Figure 31, the figure may be considered more or less typical and may be used as a planning guide. This situation, involving the Marshall Islands, was the result of a combination of circumstances involving the high energy yield of the weapon, the very low burst height, the nature of the surface below the burst point, the wind system over a large area and to a great height, and other meteorological conditions. It should be understood that the fallout pattern described above is one that can and did occur, but it is not the one that will occur in a particular location after a surface burst of a high-yield weapon.

To put the size of the BRAVO fallout pattern into perspective, Figure 32 (3) shows the Bikini-BRAVO 96-hour dose contour superimposed on a map of Pennsylvania (assuming the detonation occurred over Pittsburgh). As stated above, due to the conditions of the Bikini BRAVO shot, the actual pattern produced from a 15-Mt detonation over Pittsburgh would probably differ substantially. Fallout from a detonation over Pittsburgh would be different because (a) the burst would not necessarily be a surface burst, (b) the soil differs greatly from a coral reef, and (c) the wind structure differs. Nevertheless, a detonation producing a fallout pattern anywhere near the size of that after the Bikini BRAVO shot would definitely pose severe problems.

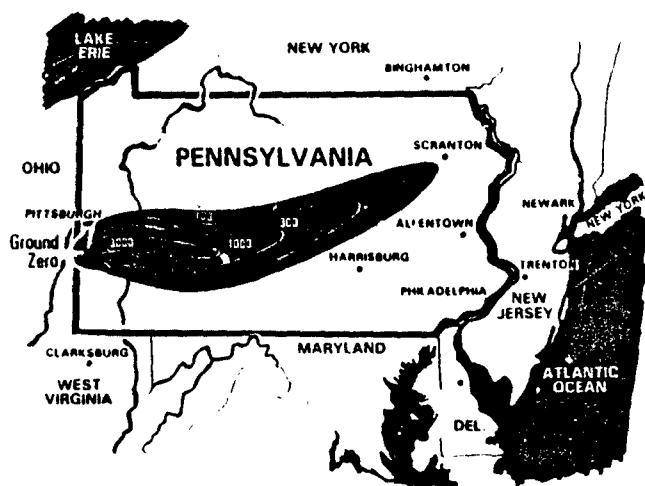


Figure 32. Fallout after Bikini BRAVO shot, superimposed on map of Pennsylvania

### Prediction of Operational Fallout

Realizing the severe limitations of the ideal fallout pattern (as indicated in actual tests), a method was developed that is used by the U.S. Army to allow better estimates of the most hazardous fallout regions, in order to allow operations to continue elsewhere. This technique is based on the known dispersion of fallout particles and its continual updating with new information on changing wind speed and direction. The typical prediction of operational nuclear fallout is illustrated in Figure 33 (10).

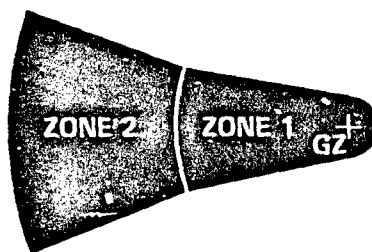


Figure 33. Typical prediction of operational nuclear fallout

The fallout prediction identifies two fallout zones and three levels of hazard. Zone I is called the Zone of Immediate Operational Concern. It defines a region wherein exposed, unprotected personnel could receive a dose of 150 rads or greater within 4 hours after the actual arrival of the fallout. Zone II, the Zone of Secondary Hazard, is a region in which exposed, unprotected personnel are expected to receive less than 150 rads within 4 hours after the arrival of fallout. But they may receive a total dose of 50 rads or greater within the first 24 hours after arrival of fallout. Outside the predicted area (Zones I and II), the exposed, unprotected personnel may receive a total dose not exceeding 50 rads in the first 24 hours after arrival of fallout. The total dose for an infinite time of stay outside the predicted area should not reach 150 rads.

These predicted zones of fallout are safe-sided estimates, since zones are larger than the actual areas on the ground that will be covered by the fallout. These zones represent areas of hazard within which, somewhere, the fallout will occur. As seen before, because of uncertainties of weather and the nuclear burst itself, the precise location of the fallout in the predicted zone is uncertain, and it must be obtained by monitoring and surveying after the fallout has settled. The lines enclosing the fallout prediction are not absolute boundaries. The zones have been developed to allow reasonably high assurance that expected fallout will not occur outside them. As these predicted zones are approached and entered from the outside, the likelihood of

encountering hazardous fallout will increase, as will the dose rates. These predictions of expected hazard areas can be quickly predicted, immediately after receiving information on an actual or planned nuclear burst. Trained personnel can complete the prediction in 3-5 min. It must be emphasized that the dose received by personnel at any location in Zones I, II, or outside the predicted area will depend on the actual dose rates at that location, the time of exposure, and the protection available (and used). A detailed version and a simplified version of this prediction method are discussed elsewhere (10).

#### Fallout Threat in the Continental United States

A complete discussion of fallout must include the results of a nuclear exchange in which many detonations would occur against a variety of near and dispersed targets in the continental United States. After a random attack on a wide range of military, industrial, and population targets, the fallout would be distributed over a very large area of the country. The actual targets of the weapons would probably depend on the conditions that led to the exchange. The size of the area affected by fallout will depend on the season, wind conditions, and other variables, but no area in the U.S. can be considered safe (11). The laws governing the fallout from this type of widespread attack are the same as those governing the fallout from a single burst. The difference lies in the fact that with widespread detonations, the fallout patterns will overlap in some places and reinforce each other. Furthermore, when a number of targets are fairly close to each other, the fallout will be fairly independent of the wind direction, since several detonations will contribute to the fallout on a given spot. Such an area is "blanketed" (8).

The final extent of the problem will depend on the winds above the United States. Figure 34 (6) exemplifies the variation of wind flow across the northeastern sector at 60,000 ft.

Figure 35 (6) demonstrates a hypothetical nuclear attack on the continental United States, in which 250 weapons are detonated over 144 military, industrial, and civilian targets. The attack totals 2500 Mt, and includes 50 devices of 20 Mt, 100 of 10 Mt, and 100 of 5 Mt.

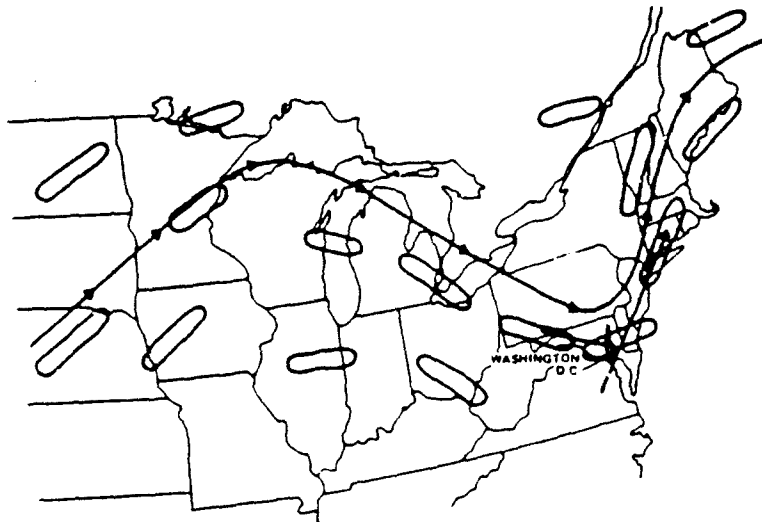


Figure 34. Variation of winds at 60,000 feet, from observations at 16 stations

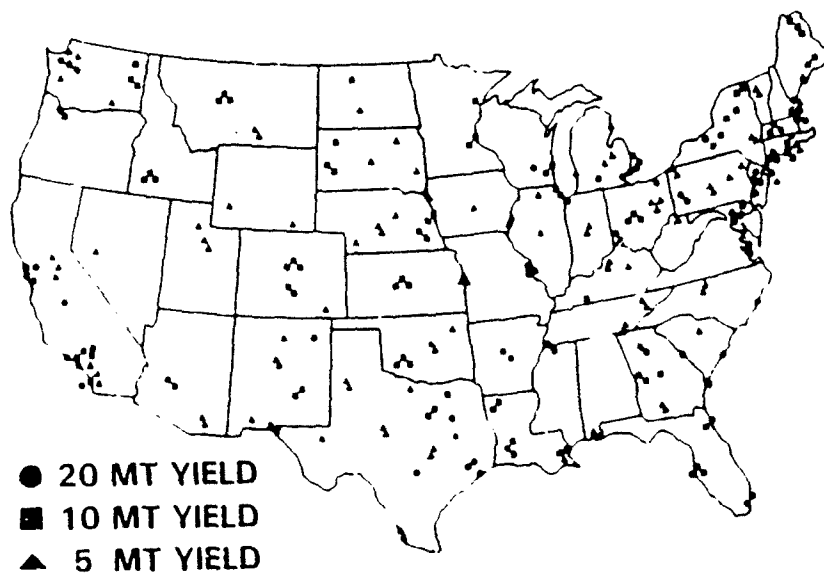


Figure 35. Pattern of hypothetical attack on the continental United States

Figure 36a-e (6) shows the fallout pattern as it moves across the country for different times after the detonation. Figure 36a shows the pattern at 1 hour after the attack ( $H + 1$ ). The fallout areas are 30-50 miles long, depending on wind conditions. In the center of these areas, the radiation levels can be greater than 3000 R/hr. Dose rates are 10 R/hr at the borders. If the dose rate does not increase, 10 R/hr at 1 hour will result in a dose of approximately 40 rads during the period of time from  $H + 1$  hour to 25 years (calculations for 25-year doses based on tables in reference 2).



Figure 36a. Hypothetical attack at  $H + 1$  hour. Dose rates exceed 10 rads/hour.

Figure 36b illustrates  $H + 6$  hours. Fallout has spread to over 40% of the country. Radiation levels have decayed by a factor of about 10. Dose rates are from about 1 R/hr along the borders to about 400 R/hr in the center. If the dose rate does not increase, 1 R/hr at 6 hours will result in a dose of approximately 30 rads during the period of time from  $H + 6$  hours to 25 years.





Figure 36b. Hypothetical attack at H + 6 hours. Dose rates exceed 1 rad/hour.

Figure 36c illustrates H + 24 hours. For dose rates greater than 0.2 R/hr, approximately 70% of the country's total area is covered by fallout. About 18% of the land area has serious fallout. If the dose rate does not increase, 0.2 R/hr at 24 hours results in a dose of approximately 19 rads during the period of time from H + 24 hours to 25 years.

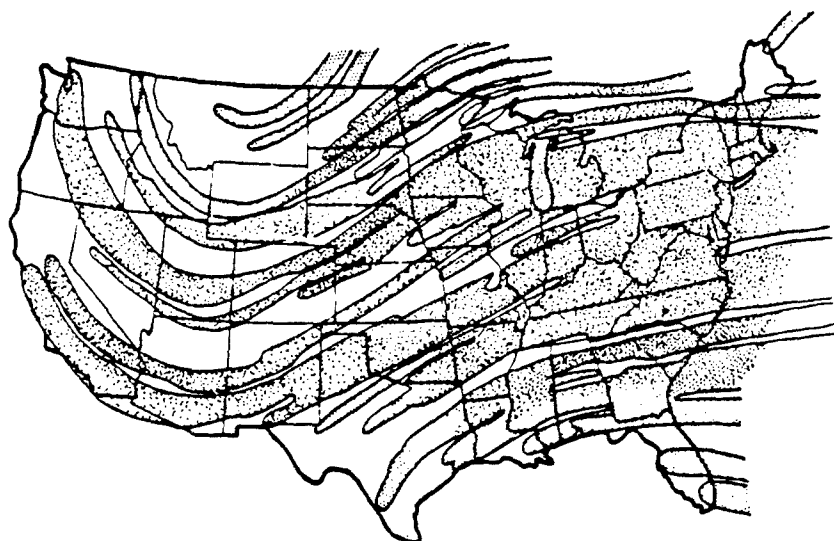


Figure 36c. Hypothetical attack at H + 24 hours. Dose rates exceed 0.2 rad/hour.

Figure 36d illustrates H + 1 week. Shortly after the first day, radiation decay begins to predominate over further depositing of fallout. The boundaries of these fallout areas gradually shrink toward the ground zeros. After about 1 week, only about one third of the nation's area is covered by fallout dose rates exceeding 0.2 R/hr. This reduction in dose rate will continue, due to the decay of the radionuclides.

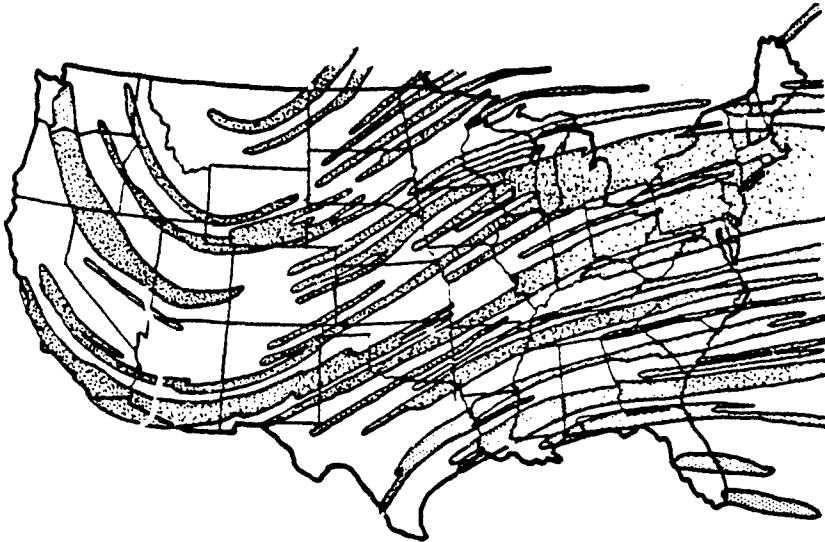


Figure 36d. Hypothetical attack at H + 1 week. Dose rates exceed 0.2 rad/hour.

Figure 36e illustrates H + 2 months. After about 2 months, only isolated elongated islands of fallout exist where the levels exceed 0.2 R/hr.

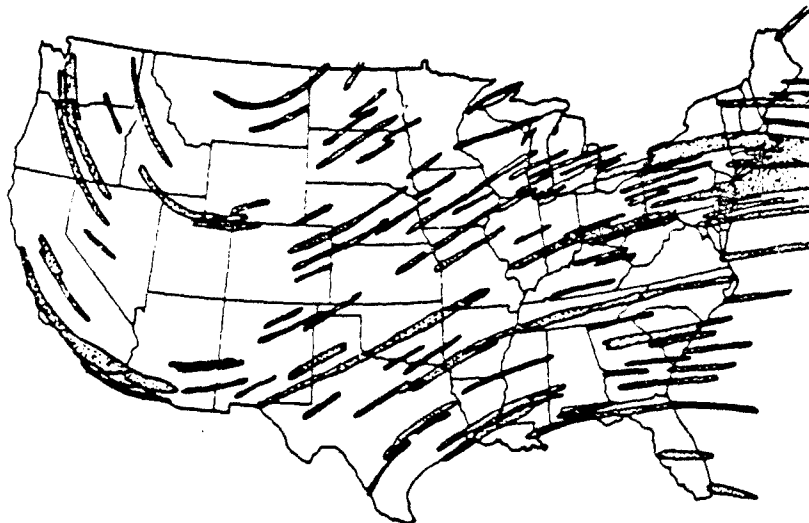


Figure 36e. Hypothetical attack at H + 2 months. Dose rates exceed 0.2 rad/hour.

It is to be emphasized that this scenario is just one possible attack pattern applied to the winds and weather conditions on a given day. The actual geographic distribution of the various levels of radioactivity in a major attack will depend on the targeting variables, enemy abort rate from malfunctions, attrition of incoming weapons from U.S. military action, duration of attack, weapons accuracy, and direction and velocity of upper winds. If a different attack pattern occurs on a different day with different weather conditions, the fallout situation will develop quite differently. Figure 37a,b (6) demonstrates a second hypothetical attack on the U.S. In this attack, 150 weapons are detonated, totaling over 384 Mt. To illustrate the variability of the wind patterns over the U.S., the same attack is evaluated on 2 different days (June 28, 1957, and July 12, 1957) with reasonably different winds. It should be noted that the axis of the fallout deposit has shifted by more than 120 degrees. On another day, the winds could swing in another direction and turn "safe" areas on these maps to areas of extreme fallout.

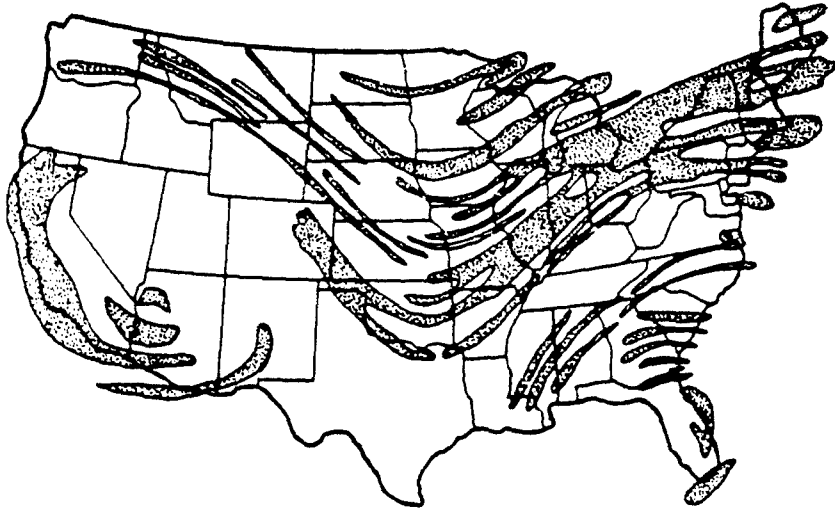


Figure 37a. Fallout pattern for winds after hypothetical attack on June 28, 1957

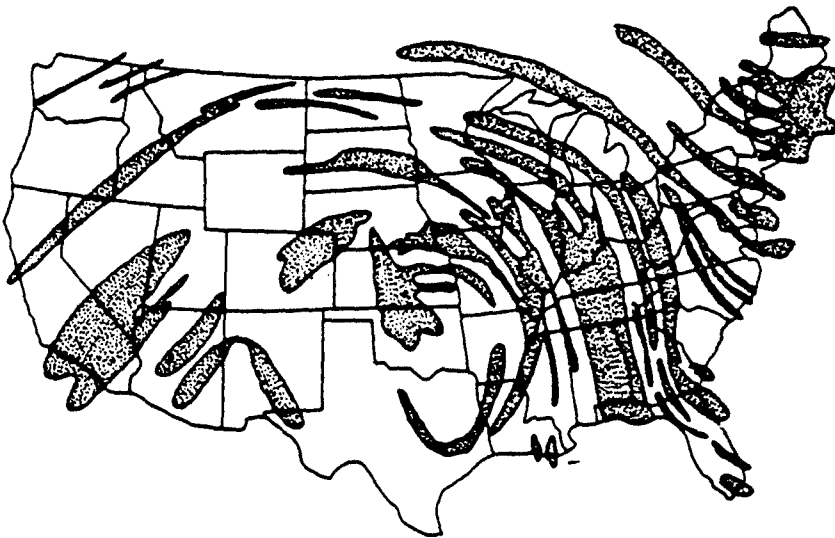


Figure 37b. Fallout pattern for winds after hypothetical attack on July 12, 1957

## RADIOLOGICAL PROPERTIES OF FALLOUT

The primary hazard from fallout is whole-body exposure to gamma radiation (1). In addition, alpha and beta radiation will be present in the fallout field. This section will review some basic principles of radiation protection, the characterization of the external hazards of fallout, and methods of protection from those external hazards.

Protection from exposure to external radiation is determined by time, distance, shielding, and common sense. Since radiation exposure, or dose, is accumulated over time, one can reduce his exposure by reducing the length of time he is near a radiation source. Another method for reducing exposure is through the use of distance. Radiation from a point will spread out in all directions. The farther one is located from a radiation source, the less radiation he will be exposed to, since the radiation becomes "dilute" with distance (i.e., less radiation per unit area). Shielding also provides protection from radiation. Although the radiation may be penetrating, it always has a probability of interacting with the material it is passing through, whether it is air, tissue, or any other substance. The more material between a person and the radiation source, the less exposure he receives. This can be accomplished by using a greater thickness of material or a more dense material. The last variable in determining protection is common sense. From a physics standpoint, common sense does not reduce the quantity of radiation, but it is very important in implementing the proper solution to a given situation, especially in the fallout field. If the prediction of fallout has taught us nothing else, it has taught us to be ready for the unexpected. As we shall see, common sense, coupled with a good understanding of the fallout problem, is one of the best defenses in reducing personnel exposure in the fallout environment.

### Protection From External Alpha Radiation

An alpha particle is a combination of two neutrons and two protons (a helium nucleus), which is emitted from a heavy nucleus at very great speeds. The alpha particles emitted from the nuclei are mono-energetic, and they will all travel to a specific distance (on the average, since there is some straggling), called the range (Figure 38).

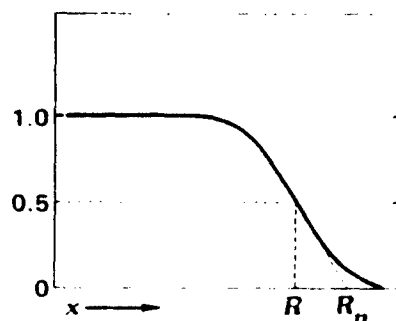


Figure 38. Number-distance curve showing relative penetration of alpha particle.  $X$  = distance traveled in the material;  $R$  = mean range or range;  $R_n$  = extrapolated range.

The range of the alpha particle in centimeters in air can be estimated from the following equation:

$$R = 0.31 E^{2/3}$$

where  $E$  is the energy in MeV. For the alpha particles emitted from the nuclei in fallout (uranium, plutonium, and their daughters), the energy of these particles is about 4-5 MeV, resulting in a range in air of approximately 3 cm. (A daughter is the resultant nuclide from a radioactive decay. For example, plutonium-239 decays by alpha emission to uranium-235. Plutonium is the parent; uranium is the daughter.) The range of an alpha particle in tissue is substantially less, and an alpha particle of at least 7.5 MeV is required to penetrate the protective layer of the skin (0.07 mm thick). Consequently, the alpha particles are readily stopped by the skin, and pose no external radiation problem in the fallout field. However, care must be taken to prevent ingestion of alpha emitters. Internal hazards of fallout will be discussed later.

Although alpha fallout poses no problem as external radiation, the short range of the alpha makes it very hard to detect. A beta-gamma instrument is usually inadequate to detect it. Very sensitive, thin-windowed (and consequently fragile) detectors are needed to conduct contamination surveys for alpha. The primary concern for external contamination by alpha is to keep it off the skin and clothing, to prevent its later ingestion through cross-contamination.

#### Protection From External Beta Radiation

Beta particles are very high speed electrons emitted from the nucleus during certain nuclear transformations. All fission fragments are beta emitters, as are most of the induced radionuclides (soil, bomb components, etc.). All beta particles emitted during radioactive decay are not monenergetic but are emitted in the form of a

continuous energy spectrum. Figure 39 shows a typical beta spectrum. As seen, most of the betas in the spectrum are of relatively lower energy. In general, the average energy of beta is one third that of the maximum energy. Since the betas are emitted with a distribution over energy, no definite range exists for beta particles.

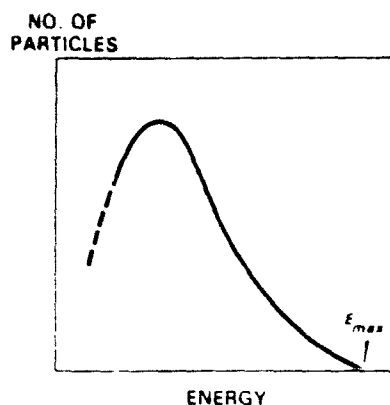


Figure 39. Typical spectrum of beta particles showing number of particles

Table 5 gives typical beta energies and their maximum ranges in air and tissue. In general, the range of the beta in air is about 12 ft (365 cm) per MeV of energy. Generally, 0.5 inch (1.27 cm) of most materials will stop all but the most energetic betas, and usually less than 0.5 inch will be required. The actual thickness of shielding that is required will decrease proportionally with the increase of a material's density.

Table 5. Approximate Beta Ranges in Air and Tissue

Energy (MeV)	Air (cm)	Tissue (cm)
0.1	13	0.14
0.5	155	0.18
1.0	380	0.46
2.0	840	0.96
3.0	1300	1.47

Although beta particles are not capable of producing external whole-body exposures, they can deposit very intense local irradiations. Beta particles can deposit about 1000 rads/sec per square centimeter per curie of activity over the length of their range. As seen in Table 5, the 0.1-MeV beta particle will penetrate well beyond the protective layer of the skin, which is 0.07 mm thick. The average maximum energy of the beta particles from the fission products is 1.2 MeV, and the absolute maximum energy probable can exceed 3 MeV (although rarely). Consequently, if the fallout particles with their fused fission fragments are allowed to remain in contact with the skin (or very near the skin separated by a very thin material), serious "beta burns" could occur. If a sizable fraction of the body should suffer serious skin damage from the beta radiation, the results would be similar to those from thermal burns, i.e., serious injury or death. Beta burn from fallout is discussed in the next section (Rongelap Contamination and Beta Burns). The primary concerns from beta radiation in the fallout field will be twofold: (a) the prevention of beta burns and (b) the prevention of ingestion of beta emitters. Internal hazards from ingestion of beta emitters will be discussed later.

#### Rongelap Contamination and Beta Burns

The Bikini BRAVO shot, being a surface burst, took large amounts of coral up into the fireball and formed limelike flakes at high altitudes (2). Within 5 hours after the detonation, the radioactivity-contaminated coral ash began falling on the Marshall Islanders. Because the weather was hot and damp, the Marshall Islanders wore little clothing. Since they were unaware of the significance of the lime "snowflakes," appreciable amounts of fission products fell on their hair and skin, and remained there for a considerable period of time. In addition, since the islanders did not wear shoes, their bare feet were continually contaminated from the fallout on the ground. After about 10 hours, the fallout cloud had thinned and was no longer visible. The visible particles were already deposited, and they presented the most serious hazard. The fallout was complete after 24 hours. Unaware of the fallout hazards, many inhabitants ate contaminated food and drank contaminated water from open containers for up to 2 days before they were evacuated. A total of 239 Marshallese were exposed.

Some Marshall Islanders bathed during the 2-day exposure period before evacuation, but other did not. Therefore, in general, optimal conditions existed for possible beta damage. In the group suffering the greatest exposure, 20% of them (13 persons) showed deep lesions, 70% (45 persons) superficial lesions, and 10% (6 persons) no lesions. Fifty-five percent (35 persons) showed some degree of epilation followed by a regrowth of hair (2).



The time sequence for those Marshall Islanders suffering from beta burns is as follows. During the first 24 to 48 hours, the more highly contaminated individuals experienced itching and burning of the skin. Those less contaminated experienced less itching and burning. Within 1 or 2 days, all skin symptoms had subsided and disappeared. After about 2 or 3 weeks, epilation and skin lesions were apparent on the contaminated areas of the body. No erythema was apparent as might have been expected, but it might have been obscured by the dark coloration of the Marshall Islanders' skin. The first evidence of skin damage was the increased pigmentation in the form of dark-colored patches and raised areas. These lesions developed on the exposed parts of the body (i.e., scalp, neck, shoulders, and depressions in forearms, feet, and limbs). The most frequently observed were epilations and skin lesions of the scalp, neck, and feet. Most lesions were superficial without blistering. No skin damage was observed under a covering of even a single layer of clothing. After 3 to 6 weeks, microscopic examination revealed that damage was most marked in the outer layers of the skin. This form of damage was due to the short range of the beta particles. The lesions formed dry scabs and then healed, leaving central depigmentation surrounded by irregular zones of increased pigmentation. Normal pigmentation spread outward in a few weeks. Regrowth of hair began in 9 weeks and was complete in 6 months. The more highly contaminated persons developed deeper lesions, usually on the feet and neck. They experienced mild burning, itching, and pain. The lesions were wet, weeping, and ulcerated, and became covered by a hard, dry scab. The majority of the lesions healed readily with the regular treatment for nonradiation skin lesions. Abnormal pigmentation existed for some time; in some cases, about a year passed before normal color was restored.

#### Physical Properties of Fallout Gamma Radiation

The primary hazard from fallout is the external whole-body exposure to gamma radiation. Gamma radiation is a decay product from both the radioactive disintegration of the fission fragments and the induced radionuclides. Monoenergetic, narrow-beam photons will attenuate exponentially as they pass through material, according to the following equation:

$$I = I_0 e^{-ux}$$

where  $I_0$  is the initial photon intensity,  $I$  is the resulting photon intensity after passing through a material of thickness  $x$  with an attenuation coefficient  $u$ . The attenuation coefficient  $u$  is a measure of the probability of a photon's interacting with the shielding material, and it depends on both the shielding material and the energy of the photon. In the fallout field, the photons that are produced will have a very broad range of energies from a few keV up to several MeV. Figure 40 illustrates how the attenuation coefficient

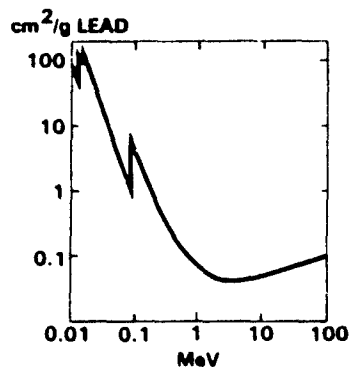


Figure 40. Attenuation coefficient for lead

of lead varies with the energy of the photon. As seen in this figure, the 0.01-MeV photons are attenuated by a factor of about 1000 times that of 1-MeV photons, whereas only a slight increase in the attenuation coefficient occurs between 1 and 100 MeV. Although the prompt gammas (which are produced within the first 60 seconds of detonation) may have energies up to around 8 MeV, the gammas produced from fallout (i.e., fission products) will have energies up to about 1-2 MeV. The ability of a material to attenuate gammas basically depends on the electron density of the material (i.e., number of electrons per cubic centimeter). Consequently, materials with high mass density and/or high atomic number make the best gamma shields. Figure 41 compares several materials and their relative ability to attenuate photons versus photon energy. It should be noted that the units used in Figure 41 ( $\text{cm}^2/\text{g}$ ) are normalized units used to remove mass density differences. It is seen that lead, which has a very large atomic number, is one of the best photon attenuators.

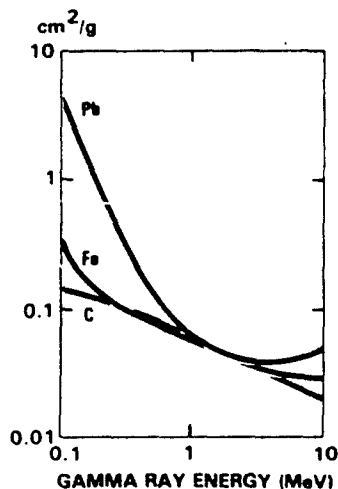


Figure 41. Mass attenuation coefficients for various materials

Figure 42 (6) compares the density and therefore relative effectiveness of various shields. As the density of a material increases, less thickness of that material is needed for effective shielding. Again, lead is one of the best shielding materials, but since it is not readily available when needed, something like iron or steel is the second best practical choice.

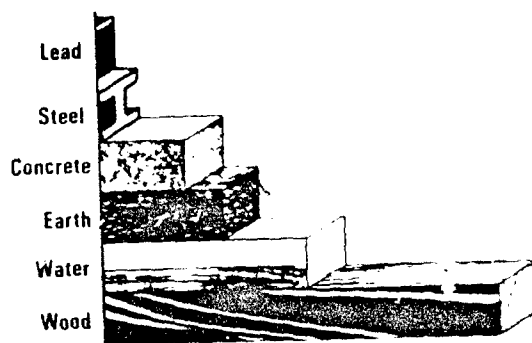


Figure 42. Relative thickness of various materials to produce equivalent shielding

Since gamma shields do not stop all the photons but rather attenuate some fraction of the initial beam, the concept of tenth thickness is used. Tenth thickness is the amount of a material needed to reduce the initial photon beam by a factor of 10. Frequently a reduction in photon energy occurs ("down scatter") rather than an actual complete absorption of the photon. In addition, for broad beams, scattering occurs into a defined area as well as out of it. Since every photon that interacts with the shield is not necessarily removed from the beam, a little extra material is needed to reduce the total number of final photons (remaining initial photons plus secondary photons) to one tenth of the initial number of photons. Table 6 gives the tenth thickness for several materials for a narrow beam (having good geometry so that most of the scattered photons leave the beam) and from a point source, which results in a broader "beam" with scattering into and out of the beam.

Table 6. Tenth Thickness for 1-MeV Photons

Material	Narrow Beam Attenuation; No Scatter (inches)	Point Source Tenth-Thickness; With Scatter (inches)
Water	13.0	24.0
Concrete	6.2	11.2
Aluminum	5.5	10.0
Iron	1.9	03.4
Lead	1.2	01.6

Since the photons in the fallout field are 1-2 MeV or less in energy and since the dose delivered is proportional to the number of photons, one can use the tenth-thickness values in Table 6 for construction of the emergency shield. Photons with energy less than 1 MeV will be attenuated to a greater degree than those at 1 MeV (see Figure 42). If we assume that all photons present are 1 MeV and construct the shield accordingly, a minimum shielding factor would result. For example, if a flux of 1-MeV photons with a dose rate of 100 rad/hr is incident on a lead shield 1.6 inches thick, the final dose rate would be 10 rad/hr. If the incident photons are of an energy less than 1 MeV, then the final dose rate would be less than 10 rad/hr. Although the actual dose rate is not known, the upper limit would be identified. In an emergency situation, a good estimated dose rate may be all that is necessary. In most cases in a fallout emergency, graphs of mass attenuation coefficients (as in Figure 41) may not be readily available, so it is also likely that graphs of the more complicated energy distribution of the gamma radiation will not be available. Consequently, the tenth-thickness values in Table 6 are very useful as quick reference numbers on shielding.

#### Time Dependence of Fallout

Since the gamma radiation in fallout is due to the radioactive decay of the fission fragments, the dose rates from fallout will decay with time. In addition, the actual rate of the decay will be determined by the actual radionuclides present in the fallout field. The overall decay rate of fallout results from the combined radiation decay rates of all the fission products and their decay products. The half-lives of the various radioactive elements range from a few seconds to many years. As time progresses after the detonation, the short-lived products decay out of the mixture, followed in turn by the longer lived and longest lived isotopes. The approximate decay rate is given by the following equation:

$$R_t = R_0 t^{-1.2}$$

where  $R_0$  is the dose rate at a unit time (normally taken to be the dose rate at 1 hour after detonation) and  $R_t$  is the dose rate at time  $t$ . Obviously,  $t^{-1.2}$  does not lend itself to a simple mental computation, but  $7^{-1.2}$  is about 0.1. Thus,  $R_7 = 0.1 R_0$ , and the seven/ten rule of thumb can be established. The seven/ten rule for fallout is as follows:

For every sevenfold increase in time after the detonation, the dose rate decreases by a factor of ten.

For example,	<u>Time</u>	<u>Dose Rate</u>
	1 hr	1
	7 hr	1/10
	47 hr	1/100
	343 hr	1/1000

Or: After 7 days, the dose rate is one tenth of the dose rate on the first day.

The accuracy of the seven/ten rule is 25% within 2 weeks and within a factor of 2 within 6 weeks. In actuality, the dose rate decreases at a faster rate than that predicted by the seven/ten rule. Therefore, any error introduced is on the side of personnel safety. If possible, measurements should be made rather than using a rule of thumb. It should be noted that the errors in the seven/ten rule could become large in the early periods after deposition if the fallout is from two or more weapons detonated some time apart, or if the fallout is produced by a clean weapon. In addition, the relationship assumes that the fallout is undisturbed during the time being considered, i.e., the fallout has not been redistributed by wind or rain.

#### Protection From External Gamma Radiation

Fallout will deposit like snow, become widely distributed on the horizontal surfaces such as the ground, roofs, trees, buildings, etc. If a person stands in the center of a large (infinite), smooth, evenly contaminated plane, about 50% of the fallout radiation reaching him would come from within a radius of 50 ft (15.2 m); 70% would come from within 150 ft (45.7 m), and 90% from within 500 ft (152 m) (1). The remaining 10% would come from beyond 500 ft (1). A real surface, such as asphalt, concrete, or the surface of a lawn, has some roughness to it. Therefore the gamma radiation from fallout on a real surface would be partially shielded, and the distances would not be so great. Half of the radiation would come from a circular area with a radius closer to 25 ft (7.6 m) than 50 ft surrounding the point of interest (1). As ground roughness increases, this radius for 50% of the exposure would continue to decrease. It should be noted that the

reduction of fallout contribution with distance due to ground roughness is more pronounced near the surface of the ground. The effect is reduced with increasing altitude (1). If personnel cannot leave the fallout area, they can reduce their exposure by one half by clearing an area of about 10 m in radius (5). In addition to clearing the area, it is beneficial to mound the dirt around the edges of the area (see Figure 43). The dirt mound offers some additional protection by attenuating some of the radiation. Allowing for ground roughness, most of the exposure will probably be delivered within a radius of about 100 m rather than the 152 m (500 ft) for the smooth infinite plane.

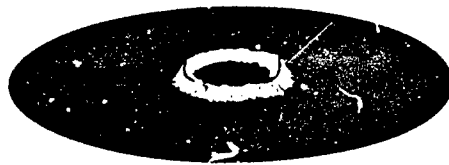


Figure 43. Mounded dirt around a clearing of 10-meter radius

Using the fact that most of the exposure will be delivered by the fallout in a radius of 100 m, we know that ground structures can aid greatly in reducing personnel exposure. In general, a person in an open, built-up city would receive about 20%-70% less dose from fallout than in the absence of shielding (2). Figure 44 illustrates how this is possible. The personnel exposure is reduced by two methods: (a) the buildings themselves act as shielding material, and (b) the height of the building increases the distance between the fallout and personnel.

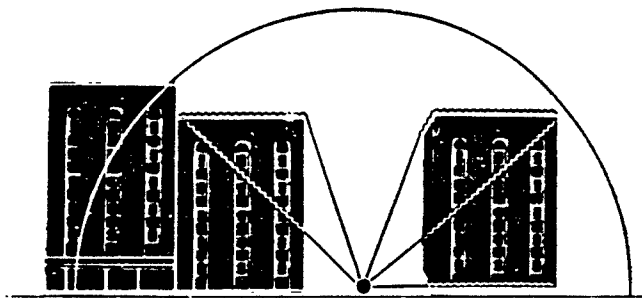


Figure 44. Dose reduction offered by buildings in a city

In a fashion similar to the above, a person standing against a building in the middle of a city block receives less radiation than at the intersection of two streets. Figure 45 diagrams this situation. In this case, the person makes the best use of the shielding offered by both the building and the distance from the fallout particles. Obviously, the best fallout protection is to remain inside the building, but if a person must go outside into the fallout field, he may minimize his exposure by the practical means discussed above.

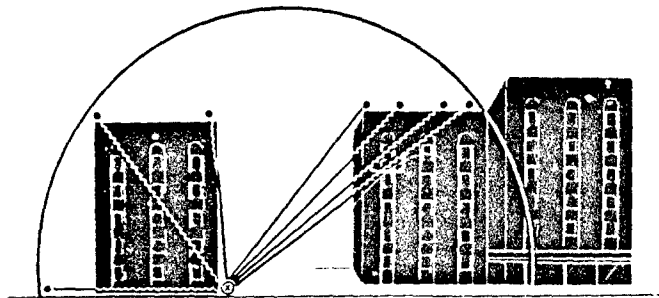


Figure 45. Best use of protection offered by a city

Large structures can be used to reduce fallout exposure through a method known as geometric shielding. Geometric shielding, in contrast to barrier shielding, is the attenuation or reduction of the exposure to a person due to his location relative to the fallout field. Figure 46 diagrams the use of geometric shielding. (Figure 45 also exemplifies geometric shielding.) As seen in Figure 46, although the building walls offer the same amount of shielding, the individuals in the center of the large building receive less exposure because the fallout is kept farther away. In general, inside a building above ground, the center of the building will offer better fallout protection than will a location next to an outside wall. It is to be noted that the reverse is true below ground, in the basement of low buildings. This is because more radiation is scattered into the center of a basement than near the walls.

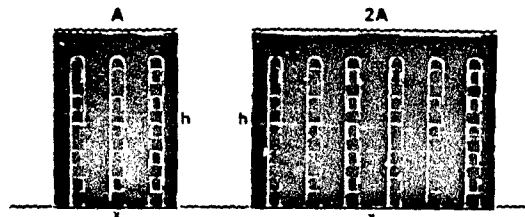


Figure 46. Geometric shielding

### Protection Factors and Transmission Factors

Individuals often perform their duties in structures that provide various amounts of protection from external gamma radiation. In evaluating these structures, the concept of tenth thickness is insufficient, since the concept was designed for unidirectional radiation whereas fallout is everywhere, resulting in multidirectional radiation. It is not sufficient to say that a particular thickness of shielding (i.e., a wall) produces a particular amount of protection inside a shelter. Thought must be given as to how the fallout is distributed around/on the ground and neighboring buildings, as well as the distances, sizes, and kinds of surfaces where the fallout is deposited. The structural characteristics and structural materials used in the buildings must also be considered. For example, the penetration characteristics of the fallout deposited on the roof of a building differ from the penetration characteristics of fallout deposited on the ground and entering only through the sides of the building.

The terms "protection factor" and "transmission factor" are used to describe the protection offered by these structures. Protection factor is the relative reduction in amount of radiation that would be received by a person if he were unprotected. Figure 47 illustrates the protection factor. The individual in the open receives 100% of the exposure. By entering the shelter, he now receives 1% of the exposure. The protection offered by the shelter is 100; in other words, the exposure has been reduced by a factor of 100. The protection factor compares the expected radiation level in the location of interest (shelter) to the level that would exist at 3 ft above a smooth, infinite plane contaminated with the same amount of fallout per unit area (1). It is conceptionally related to the ratio of the outside dose/exposure to the inside (protected) dose/exposure (see following text under note on Protection Factors and Transmission Factors) (1).

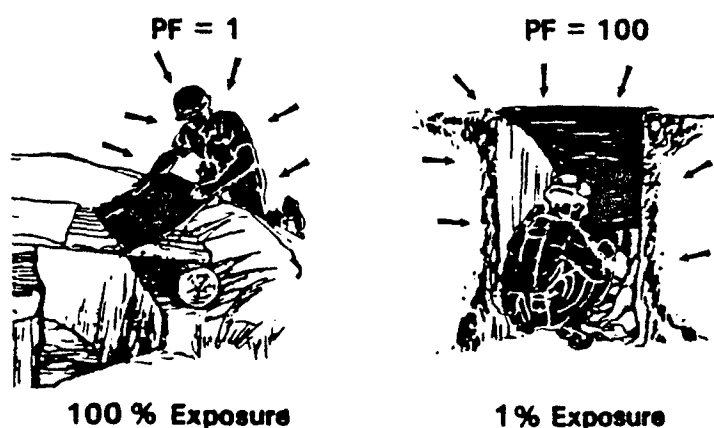


Figure 47. Shelters with protection factors of 1 and 100



The transmission factor is conceptionally the inverse of the protection factor. It refers to the fraction of the radiation that is allowed to pass through the structure. The transmission factor for the shelter in Figure 47 is 0.01; in other words, only 1% of the outside dose/exposure exists inside. Table 7 gives various transmission factors assigned to structures that are routinely used by combat ground forces. These factors were calculated to indicate the shielding given by the structures to personnel in the structures from residual radiation; the factors may differ from other published transmission factors, depending on the radiation environment considered (i.e., transmission factors for prompt gamma radiation).

Table 7. Typical Transmission Factors for Residual Radiation

Structure	Transmission Factor
M60 tank	0.04
M48A2 tank	0.02
M41 tank	0.1
M113 armored personnel carrier	0.3
XM 104 SP howitzer	0.5
M107 SP gun	0.4
M108 SP howitzer	0.3
M109 SP howitzer	0.2
M110 SP howitzer	0.4
XM106 SP mortar	0.3
M125A SP mortar	0.3
M114 recon vehicle	0.3
M116 cargo vehicle	0.6
M548 cargo vehicle	0.7
M88 recovery vehicle	0.99
M578 recovery vehicle	0.3
M577 command post carrier	0.3
M551 armored recon	0.2
M728 combat engr vehicle	0.04
1/4-ton truck	0.8
3/4-ton truck	0.6
2 1/2-ton truck	0.6
4-7-ton truck	0.5
Multistory building, upper floor	0.01
Multistory building, lower floor	0.1
Frame house, first floor	0.6
Frame house, basement	0.1

#### Note on Protection Factors and Transmission Factors

To compare the adequacies of structures and vehicles at different locations, it is necessary to compare their shielding abilities to a reference standard. Normally the standard for fallout radiation is the radiation dose that exists 3 ft above a smooth infinite plane containing a given amount of fallout per unit area at 1 hour after

detonation (13). The gamma spectrum of fallout radiation used is that existing at 1.12 hours after fission (see Figure 48). A measurement at 3 ft above ground level (about waist high) approximates the average whole-body dose that a person would receive if he were standing in the open in the contaminated area at the location of the measurements (5, 13). All protection factors assigned by the Defense

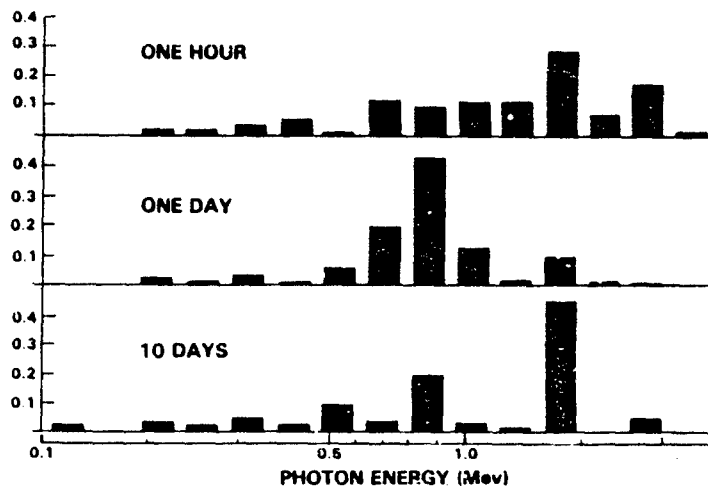


Figure 48. Change in the fission-product gamma-ray spectrum with time

Civil Preparedness Agency were based on the above reference standard. A protection factor is defined as the ratio of the "standard" radiation level to the radiation level inside the shelter (13). It is technically not the ratio of the outside exposure/dose to the inside exposure/dose. Calculations indicate that the protection factor for a real surface (as opposed to the ideal plane) is about 1.5 and that it greatly depends on location (1).

The transmission factor has a broader use. It is often used for different types of radiation (e.g., prompt neutrons, prompt gammas, and residual radiation), and will subsequently show variability based on the choice of incident radiation. For example, for an armored personnel carrier, the prompt neutron transmission factor is 0.7, prompt gamma is 0.7, and residual is 0.3 (14). When the standard for fallout radiation is used (as defined above), the protection factor and transmission factor are the multiplicative inverse of each other.

It should be noted that since the protection factors and transmission factors are based on standards, the actual value that is measured in the field for a given fallout location differs from the assigned value. The assigned protection factor (see Table 7) does not take into account the actual pattern deposited, the redistribution due to weathering (wind and rain) or gravity (sliding off roofs), changes in

penetration characteristics of the radiation with time (Figure 48) (13), or the effects due to blast and/or thermal radiation from the explosion. Nevertheless, the protection factors (and transmission factors) are useful tools for planning. The limitations that can be expected do point out the importance of measuring the radiation levels inside a fallout shelter, since they may differ from those expected.

## INTERNAL HAZARDS FROM FALLOUT

Both early and delayed fallout are potential internal hazards. The internal hazards of early fallout are not as serious as the primary and secondary hazards of external whole-body gamma irradiation and beta burns. The primary hazard of delayed fallout is internal. Although many factors govern the potential fallout problem (type of weapon, yield, height of burst, height of cloud, distribution of radioactivity in the cloud, radioactivity associated with various particle sizes, rate of fall of particles, and meteorological conditions), the controlling factor for the long-term fallout problem and the subsequent problem of internal hazards is the length of time the particles stay in the air. The size of the particles formed and the height of ascent determine how long the particles remain in the air.

Global distribution of fallout occurs when the very fine particles reach very high altitudes. All bursts above ground can cause long-term fallout. Airbursts have approximately 100% delayed fallout (2). Delayed fallout from a surface burst depends on the type of surface under the detonation. Land surface bursts result in about 40% delayed fallout, whereas fallout from water-surface bursts is approximately 70% delayed. For tactical or low-yield weapons (less than about 100 kt) detonated close to the ground, the fallout problem usually does not last longer than a few weeks (2).

### General Concept of Internal Hazards

Fallout may enter the body and become an internal hazard. If this occurs, the concern for the type of radiation is the opposite of the concern for external exposure. Alpha particles, because of their relatively large size, produce localized regions of extremely high ionization that result in extensive and localized damage to tissue. Gamma radiation, on the other hand, because of its greater ability to penetrate tissue, is of relatively less concern. A photon travels much farther than an alpha particle before it interacts; at the time of interaction, it produces much less damage per unit path length than an alpha particle does. The result is a lower average dose. In addition, depending on the photon's energy, a high proportion of photon may leave the body without interacting in the tissue. Beta radiation is intermediate. Although the damage that beta radiation produces per unit path length is comparable to the damage a photon produces when it interacts, the beta radiation travels a relatively short distance in tissue, thus producing relatively high average doses.

Internal exposure causes great concern because radiation exposure of organs and tissues from an internal source is continuous exposure, and nuclides tend to collect in critical organs (e.g.,  $^{131}\text{I}$  in thyroid). The radionuclide is subject to depletion only by physical decay or by biological elimination. The actual internal dose rates are highly dependent on the circumstances surrounding the pathway by which the radionuclide becomes an internal hazard; as a result, they may not be readily predictable. A radionuclide becomes internal by

inhalation, ingestion, or injection through a wound. The actual fate of the radionuclide depends on its chemical nature. Radioisotopes follow the same metabolic processes as the stable isotopes of the same element; for example, radioactive iodine goes to the thyroid.

Elements not normally found in the body behave like those with similar chemical properties that are normally present in the body. For example, strontium, barium, and cerium act like calcium by going to the bone. But since these elements are only chemical analogs, they will act differently and will deposit in tissues in which the original element may not be present; i.e., cerium, in addition to going to the bone, will go to the liver, spleen, and other tissues, and a greater percentage of strontium will deposit in the soft tissue relative to the percentage of calcium in soft tissue.

Any element that does not tend to concentrate in a particular part of the body is eliminated rapidly by natural processes. The probability of serious pathological changes caused by ingestion depends on the amount of radionuclide deposited, energy of radiation emitted by the radionuclide, type of radiation emitted, and length of time the source is in the body.

Of particular interest are the bone seekers: plutonium, strontium, cerium, and barium. Bone seekers are radionuclides that tend to concentrate in the bone. They are of serious concern because they can cause radiation damage to bone marrow, resulting in leukemia and other hematological abnormalities. They can also cause actual bone damage, producing bone necrosis and bone tumors.

#### Inhalation

At the time of a nuclear detonation, particles of many different sizes are produced and become airborne. Early fallout particles range in size from 20 microns to 1 centimeter. Delayed fallout particles are smaller. Particles larger than 10 micrometers are the most hazardous. These particles do not reach the lungs because the nose is almost totally efficient in filtering particles larger than 10 microns, and about 95% efficient for particles of 5 microns (2). Obviously, one would not want to let fallout particles accumulate in the nose and remain there because damage from energetic betas could result. Table 8 gives the efficiency of various common household items and personal items that can be used as an emergency filter against aerosols with a particle size of 1 to 5 micrometers.

Table 8. Efficiency of Common Household Items Against Particle Sizes of 1-5 Micron

Item	Number of Thicknesses	Approximate Efficiency (%)
Handkerchief, man's, cotton	16	94
Toilet paper	3	91
Handkerchief, man's, cotton	8	90
Handkerchief, man's, crumpled	-	88
Bath towel, cotton terry cloth	2	85
Bath towel, cotton terry cloth	1	74
Shirt, cotton	2	66
Handkerchief, woman's, cotton	4	56
Slip, rayon	1	50
Dress material, cotton	1	48
Shirt, cotton	1	35
Handkerchief, man's, cotton	1	28

Soluble particles and insoluble particles entering the lungs behave in slightly different ways. Generally, 25% of the soluble airborne particulate is exhaled, 50% remains in the upper respiratory tract and is swallowed within 24 hours, and the remaining 25% is absorbed (15). Twenty-five percent of the insoluble airborne particulate is exhaled, 50% remains in the upper respiratory tract and is swallowed within 24 hours, 12.5% enters the deep respiratory tract and is swallowed within 24 hours, and the remaining 12.5% remains in the deep respiratory tract and is eliminated with a biological half-life of 120 days (15). Since many of the contaminated particles of fallout are relatively insoluble, they are not transported to the blood (2). Particles remaining in the lungs are removed by cellular or lymphatic transport. Those removed by the lymphatic system accumulate in the tracheobronchial lymph nodes, thus causing intense localized radiation doses. (2).

#### Ingestion

Ingestion of fallout particles occurs in two sources: contaminated mucous from the upper respiratory tract, and contaminated food and water. Solubility of fallout material is the major factor in determining the distribution and thus the resultant dose within the body. The solubility varies, depending on (among other factors) the surface over which the detonation has occurred. Fallout material collected in soil samples at the Nevada Test Site is quite insoluble (12).

However, it is likely that activity actually present in drinking water is principally a soluble form (12). Water collected from a well and a cistern on the island of Rongelap about 21 months after the March 1, 1954 fallout was found to have about 80% of the initial activity in the filtrate, with an undetermined amount settling on the bottom (12). Other data suggest that the material was about 10% to 20% soluble in water (12).

Like most fission products, uranium and plutonium are in the form of oxides, and do not dissolve well (2). As oxides, strontium and barium are about 10% soluble; after entering the blood, they go to the bone (2). Iodine is soluble; it readily enters the blood and goes to the thyroid (2). Although large amounts of radionuclides pass through the kidneys, they do not greatly affect that organ (2). The large intestine receives a reasonable portion of the relative dose to body organs (12). These doses to the large intestine occur because of the length of time the insoluble radionuclides remain in the large intestine while waiting to be excreted.

#### Injection

The amount, form, and subsequent effect of radionuclides entering the body through an injection or wound depend entirely on the situation. Action taken to reduce the overall potential hazard from the injection should correspond to the normal methods of wound decontamination.

#### Isotopes of Concern

Although a wide range of radionuclides is produced in a nuclear detonation, only a few present particular problems. The relatively short-lived radioisotopes produced from sea and ground activation are listed in Table 9 (2). These isotopes are short-lived and pose no particular internal problems. Aluminum is a concern until about one-half hour postdetonation, and manganese and silicon are a concern up to about 10-20 hours. Thereafter, sodium is the concern for up to a few days (4, 5).

Table 9. Most Common Ground-Induced Radionuclides

Isotope	Radiation	Half-Life
Sodium-22	Beta, gamma	15.0 hr
Chlorine-38	Beta, gamma	37.0 min
Manganese-56	Beta, gamma	2.6 hr
Aluminum-28	Beta	2.3 min
Silicon-31	Beta	2.6 hr

Of the 36 elements produced by the fission process and by subsequent decay of fission fragments, only a few are of concern. Based on their potential hazard, these isotopes can be divided into three groups (2). Group I contains iodine-131, which is a problem for only the first few weeks because it has a relatively short half-life. The isotopes in Group II are strontium-89 and -90, cesium-137, and barium-140. These isotopes enter the stratosphere from moderate- and high-yield weapons. Due to their long half-lives, they persist for years and are the most significant problem of long-term fallout. Group III isotopes are cerium-144, yttrium-91, and other related rare earth elements. These isotopes are similar to Group II but are less significant.

Bomb materials can be activated. Of primary concern are the isotopes of zinc, copper, magnesium, and (to a lesser extent) iron (2), which are a concern only in early fallout. Other bomb materials include the unspent fuels uranium, plutonium, and tritium (from the lithium in the lithium deuteride). These isotopes remain and contribute to the problem of long-term fallout.

Two other isotopes are produced from the interactions of neutrons with the air. Carbon-14 is produced from the nitrogen-14 in air. Nitrogen-14 absorbs a neutron, and the subsequent compound nucleus (nitrogen-15) decays by emitting a proton and producing carbon-14. Tritium, to a minor extent, is also produced from the unstable nucleus of nitrogen-15. Nitrogen-15 can decay to stable carbon-12 by emitting a tritium nucleus.

#### Particular Internal Exposure Problems

Iodine-131: Although several isotopes of iodine are produced (2), the other isotopes (iodine-132, -133, and -134) have half-lives of less than 1 day (2.26 hr, 20.3 hr, and 52 min, respectively). They are a problem only if ingested very early after the detonation. Iodine-131, with a physical half-life of 8 days, will concentrate in the thyroid, where it has a biological half-life of 80 days. Radioactive iodine will be readily ingested from milk from cows that have eaten contaminated forage.

Current metabolic data for iodine (16): Reference man (a model of man used for reference by the International Council on Radiation Protection) (17) contains a total-body content of 11 mg of iodine, with 10 mg residing in the thyroid (16). Bodily intake through food and fluid is estimated to be 0.2 mg per day. Actual uptake of radioactive iodine from the blood depends greatly on the availability of stable iodine in the daily intake. Absorption from the gastrointestinal tract into the blood (occurring mainly in the small intestine) is assumed to be 1 (100% absorption) for all commonly occurring compounds of iodine. For iodine particulates of 1  $\mu$ m activity mean aerodynamic diameter (AMAD) that are inhaled, 30% remain in the nasal passage (half of which go to body fluids and half to the gastrointestinal tract through swallowing), 8% are retained in the trachea and bronchial tree (of which 95% enter body fluids and



the remainder enter the GI tract), and 25% are retained in the pulmonary parenchyma (of which 80% are absorbed into the body fluids and 20% are transported by the pulmonary lymphatic system to the pulmonary lymph nodes). For particles of sizes other than 1  $\mu$ m AMAD, the fraction of the retained inhaled particles depends on their actual average size. Information on fraction of retention per particle size in each of the three regions (nasal passage, trachea and bronchial tree, and pulmonary parenchyma) can be found in reference 16. Of the total iodine absorbed into the blood, a fraction of 0.3 is assumed to enter the thyroid. The remainder is assumed to be excreted. Iodine retained in the thyroid has a half-life of 120 days, and is lost from the thyroid as an organic iodine. Organic iodine is assumed to be uniformly distributed throughout the body (excluding the thyroid), and is eliminated with a biological half-life of 12 days. For each microcurie of iodine-131 deposited in the thyroid, an estimated dose of 6.5 rem will be delivered over a 50-year period (18). (Fifty years is considered the lifetime exposure.)

Strontium-90: Strontium-90 is formed (a) directly from fission with a yield of 30-40 strontium-90 atoms per 1000 fissions, and (b) through the decay of the gaseous precursors rubidium and krypton (2). Strontium-90 and its daughter yttrium-90 are beta emitters with half-lives of 29 years and 64 hours, respectively. Strontium accounts for a considerable portion of fallout that is several years old.

Strontium-90 is an internal hazard because of its long-term retention in the skeleton. Its biological half-life for removal from the skeleton is 49.3 years. Strontium is chemically similar to calcium, but has a very complex metabolism. The human metabolism discriminates against strontium. Two to ten times less strontium than calcium is stored by many persons because of the processes of biological transfer processes. The rate of deposition of calcium and of strontium is greater in growing children.

Most of the strontium-90 in delayed fallout is ultimately brought to earth by rain or snow, and it makes its way into the human body primarily (directly and indirectly) through plants. So the accumulation of strontium-90 in the human body is determined by the availability and proximity of strontium to the root system of plants. Most strontium deposited on undisturbed soil is close to the surface. Strontium deposited from delayed fallout is mostly in a soluble form, readily available to plants. In addition, growing plants retain a certain amount of the strontium-90 deposited on their surfaces. The plants containing strontium can be either eaten by man (direct ingestion) or eaten by animals. Since very little strontium is retained in soft tissue, the amount of strontium-90 retained in the edible parts of animals is negligible. In addition, the ratio of strontium-90 to calcium in milk is much less than that in the feed. Thus, the animal acts as an important barrier to the consumption of strontium-90 by man. Although less strontium than calcium is found in cow's milk, about three quarters of the calcium in the average diet (and hence a large fraction of the strontium) is obtained through milk and milk products in the United States.

Current metabolic data for strontium-90 (16): Reference man (17) has a total body content of 0.32 g of strontium, of which only trace amounts (0.0033 g) lie outside the skeleton in soft tissue (16). Bodily intakes of strontium through foods and fluids is estimated to be 1.9 mg. The fractional uptake into the blood from the GI tract for soluble strontium salts and dietary strontium has a range of values. A fractional uptake of 0.3 is assumed for purposes of dose assessment. In inhalation of strontium particles of 1  $\mu$ m AMAD, 30% are retained in the nasal passage (of which 50% go to body fluids and 50% go to the GI tract through swallowing), 8% are retained in the trachea and bronchial tree (of which 95% enter body fluids and the remainder enter the GI tract), and 25% are retained in the pulmonary parenchyma (of which 80% are absorbed into body fluids and 20% are transported by the pulmonary lymphatic system to the pulmonary lymph nodes). The strontium that does enter the body is assumed to distribute through the volume of the mineral bone. The estimated dose to the bone for 1 microcurie deposited in the bone is 3.6 rem in 13 weeks and 320 rem in 50 years (18). For strontium retained in the lungs, an estimated dose is 2.9 rem in 13 weeks and 4.1 rem over 50 years (18).

Cesium-137: Cesium-137 is significant in fallout that is more than 1 year old (2). It is an abundant fission fragment product, occurring with a frequency of about 50-60 cesium atoms per 1000 fissions, and it is also produced from the decay of xenon-137. Cesium-137 has a physical half-life of 30 years. Elemental cesium is normally found in the body in small traces. Since it resembles potassium chemically, it is found rather uniformly distributed throughout the body, with higher concentrations in muscle. Cesium has a relatively rapid turnover; its biological half-life varies from 50 to 200 days, depending on a person's diet, age, sex, race, and body weight. Cesium would be ingested mainly in food. If cesium in plants has been absorbed through the roots, then the dose that can be delivered will be in proportion to the amount of cesium in the ground. If the cesium is on the leaves of the plants, the internal dose is in proportion to the rate of descent of the fallout. The overall potential hazard from the cesium-137 is less than that of strontium.

Current metabolic data for cesium (16): Reference man (17) contains a total-body content of 1.5 mg, of which 0.57 mg is found in the muscle and 0.16 mg in the bone (16). Bodily intake through food and fluid is estimated to be 10  $\mu$ g per day. Fraction uptake to the blood from absorption from the GI tract is assumed to be unity for all compounds of the element. For the inhalation of 1- $\mu$ m AMAD particles, the retention is the same as described for iodine and strontium: 30% nasal passage, 8% trachea and bronchial tree, and 25% pulmonary parenchyma, each with the same fraction to the GI tract, body fluid, and lymph. Although the cesium is distributed uniformly throughout the body, the highest concentrations are found in muscle. A variety of biological half-lives have been reported, from 50 to 200 days. For dose-assessing purposes, current methodology assumes a two-compartment model of retentions, with both uniformly distributed throughout the body. One compartment has a

biological half-life of 2 days and the other a half-life of 110 days. Although the fraction in the first compartment has been found to vary, a value of 10% is assumed to exit, with a 2-day biological half-life. An estimated dose for cesium based on a 1-microcurie retention is 0.04 rem to the total body and 1.5 rem to the lung. Both exposures are evaluated over a 50-year period (18).

Plutonium-239: The decay of plutonium is accompanied by an energetic alpha of approximately 5.1 MeV and a low-energy gamma of 0.0516 MeV. Since the physical half-life of plutonium is 24,000 years, it has a relatively low activity. However, plutonium is a serious internal hazard for two reasons: it emits an energetic alpha, and it has a long biological half-life (100 years for the skeleton and 40 years for the liver). Plutonium can enter the body through the lungs, the digestive tract, or breaks in the skin. Although plutonium is hard to detect, the actions normally taken to prevent ingestion and inhalation of fission products will help reduce the hazards of plutonium.

Current metabolic data for plutonium-239 (16): Reference man (17) does not provide data for plutonium concentrations in man, although there are measurable quantities in food and in human tissue from the fallout from testing of nuclear weapons (16). At present, the fraction absorbed from the GI tract into the blood is assumed to be  $1 \times 10^{-5}$  for oxides and hydroxides and  $1 \times 10^{-4}$  for all other commonly occurring compounds of the element. Increased absorption occurs in very young persons.

Inhalation of plutonium as an oxide is described differently from inhalation of other plutonium compounds. Thirty percent retention in the nasal passage of inhaled particles (1  $\mu$ M AMAD) of plutonium compounds other than plutonium oxide is assumed. Ninety percent of the retained plutonium is transported to the GI tract; the remainder enters body fluids. Retention in the trachea and in the bronchial tree is 8%, half of which is absorbed by the GI tract, and half into body fluids. Pulmonary parenchyma retention is 25% of the inhaled plutonium, of which 5% is transported by the lymphatic system to the pulmonary lymph nodes, 80% is transported by the particle transport processes (e.g., mucociliary transport) to the GI tract, and the remaining 15% is absorbed into body fluids. For plutonium oxide, although 30% of plutonium is retained in the nasal passage and 8% is retained in the trachea and in the bronchial tree, 99% from each site is transported to the GI tract and 1% is absorbed into body fluids. Similarly, although 25% is retained in the pulmonary parenchyma and 80% goes to the GI tract, 15% is transported by the lymphatic system to the pulmonary lymph nodes and only 5% is absorbed into the body fluids.

The principal organs for depositing of absorbed plutonium are the liver and the skeleton. Although a wide variability exists, the assumed fractions of deposit for dosimetry purposes are 0.45 in the liver, 0.45 in the bone, and 0.1 in all other tissues and early excreta. For bone dosimetry, plutonium deposited in the skeleton is assumed to be uniformly distributed over the bone surface. Dose estimates based on the retention of 1 microcurie in the organ are 180 rem in 13 weeks and 30,000 rem in 50 years for bone; for plutonium retained in the lung, it is 230 rem in 13 weeks, and 2000 rem in 50 years to the lung (18).

Uranium: The isotopes of uranium (uranium-235, uranium-236, and uranium-238) that could be in the fallout field are all alpha emitters (energies of 4.4 MeV, 4.5 MeV, and 4.2 MeV, respectively) (2). Each has an extremely long half-life ( $7.04 \times 10^8$  years,  $2.34 \times 10^7$  years, and  $4.468 \times 10^9$  years). Since their half-lives are so long, they have low activity. The critical organs for uranium are the lower large intestine and the kidneys. Although uranium can act as a chemical poison in the kidneys, this will not be a primary concern because of the small amount taken in.

Current metabolic data for uranium (16): Reference man (17) has a total body content of 90 ug, of which 59 ug is in the skeleton and 7 ug in the kidneys. Bodily intake through food and fluid is assumed to be 1.9 ug per day. Although absorption by GI tract and deposit in lung vary greatly for uranium compounds, we will consider here only uranium oxides because they are the forms most likely to be found after a detonation (2). Uranium oxides are relatively insoluble; the fraction of uranium absorbed into the blood from the GI tract is assumed to be 0.002. For inhalation, a retention of 30% (1-um AMAD particles) is assumed for the nasal passage and 8% for the trachea and bronchial tree. In each of these, 99% of the intake is transported to the GI tract and the remainder is absorbed into body fluids. In the pulmonary parenchyma, 25% of the inhaled uranium oxide is retained; 80% of that amount is transported to the GI tract, 15% is retained in the pulmonary lymph, and 5% is absorbed.

The following assumptions are made concerning the absorbed uranium: (a) fractions of 0.2 and 0.023 go to the bone with biological half-lives of 20 and 5000 days, respectively; (b) fractions of 0.12 and 0.00052 go to both the kidney and all other body tissues with biological half-lives of 6 and 1500 days, respectively; and (c) any remaining uranium (.65648) is excreted.

Regarding bone dosimetry, the uranium is assumed to be uniformly distributed throughout the volume of mineral bone. Over a period of 50 years, dose estimates are 160/170 for 1 microcurie of uranium-238 and uranium-239 deposited in the bone, and 1700/1600 rem for an equal amount deposited in the lung (18).

Carbon-14: Carbon-14 results from the interaction of fast neutrons with nitrogen in the air (2). It is a beta emitter, and has a physical half-life of 5,730 years. Carbon-14 will incorporate into any material that uses carbon. Carbon-14 forms carbon dioxide in the atmosphere, which is incorporated into plants and later into the human body. In the body, carbon-14 becomes uniformly distributed in soft tissue, but its radiobiological effect is small compared to that of strontium-90.

Current metabolic data for carbon (16): Reference man (17) contains 16 kg of carbon, of which 9.6 kg is in adipose tissue, 3.0 kg in skeletal muscle, and 0.7 kg in bone (16). Adipose tissue has a concentration of carbon about three times that of whole body concentrations; no other organ or tissue will concentrate a significant amount of stable carbon. Bodily intake of carbon in food and fluid is 0.3 kg per day. Although some carbon compounds are not completely absorbed into the GI tract, the fraction taken into the blood from the GI tract is assumed to be 1.

The forms of carbon most likely to be inhaled are carbon monoxide and carbon dioxide. It is assumed that 40% of inhaled carbon monoxide is instantaneously bound to the hemoglobin, and 60% is exhaled. Carbon monoxide bound to hemoglobin is uniformly distributed throughout all organs and tissues of the body, and is retained with a biological half-life of 200 minutes.

All carbon dioxide entering the respiratory system is believed to be transferred to the blood. The carbon dioxide is then uniformly distributed throughout all organs and tissues of the body. Retention is as follows: 18% has a biological half-life of 5 minutes, 81% has a biological half-life of 60 minutes, and 1% has a biological half-life of 60,000 minutes. The 60,000-minute half-life represents that fraction of inhaled carbon dioxide that becomes involved in biosynthesis or is exchanged with bone carbonates. For dose assessment, all inhaled or ingested carbon-14-labeled compounds are assumed (a) to be instantaneously distributed throughout all organs and tissues of the body, and (b) to be retained with a biological half-life of 40 days. Over a 50-year period, the estimated dose for 1 microcurie deposited in the total body is 0.0006 rem; for the same amount deposited in the lung, the estimated dose is 0.20 rem (18).

Tritium (hydrogen-3): Tritium is a beta emitter of very low energy and a physical half-life of 12.3 years. It is found chiefly as a residue of the thermonuclear process (2). Because tritium rapidly becomes tritiated water, it may be ingested through food or drink. Once ingested, tritium is uniformly distributed throughout the body. The hazard of tritiated water can be reduced by diluting with ordinary water. Internal doses from tritium are relatively unimportant compared to the internal or external hazards from the fission products.

Current metabolic data for tritium (16): Reference man (17) has a total hydrogen content of 7000 g, of which 6300 g is in the soft tissue. Much of the hydrogen found in the body is associated with the body water. The body water content of reference man is 42,000 g, and water accounts for 80% of the mass in a number of soft tissues. Bodily intake of hydrogen and water are 350 g and 3000 g per day, respectively. Absorption of tritium-labeled organic compounds can vary, and a considerable portion of particular organic molecules may be broken down into tritiated water in the GI tract. For dose-assessing purposes, we can assume complete absorption of ingested tritium-labeled compounds and tritium-labeled water as well as inhaled tritium-labeled organic vapors and tritium-labeled water. Unless a particular tritium-labeled organic compound is identified and its metabolic path is known, it is usually assumed to act as tritium-labeled water. Tritium-labeled water is uniformly distributed among all soft tissues at any time following intake. Retention of tritium has a biological half-life of 10 days. Estimated doses based on the retention of 1 microcurie of tritium uniformly distributed throughout the total body is 0.0002 rem in 13 weeks.

#### Experience of Internal Hazards From Early Fallout (2)

Evidence indicates that contamination of the Marshall Islanders was by ingestion instead of inhalation. They ate food and drank water from open, contaminated sources for up to 2 days before being removed from the islands. But only iodine, barium, and strontium isotopes and the rare earth elements were found to persist; all other elements were rapidly eliminated from the body. The body burden of radioactive materials among the more highly contaminated inhabitants was never large, and it decreased fairly rapidly in the course of 2 or 3 months. Activity of the strontium isotopes fell off more slowly. Although the Marshall Islanders lived for almost 2 days under conditions of maximum probability of contamination of food and drink and although they took few steps to protect themselves, the amount of internally deposited radionuclides was small.

The Marshall Islanders received whole-body gamma exposure up to 175 rem (2). The short-term effects from internal sources from early fallout are minor compared to those due to external radiation. However, delayed effects have been seen. Only one case of leukemia was reported, and no thyroid abnormalities were detected before the year 1963 (approximately 9 years after the detonation). But by 1966, 18 cases of thyroid abnormalities were reported. This number increased to 22 in 1969 and to 28 in 1974. Most of the thyroid lesions occurred in children who were younger than 10 years old at the time of exposure (in 1954). Of those 28 persons with thyroid lesions, 3 developed malignancy, 2 suffered hypothyroidism, and all others developed benign nodules.

### Potential Magnitude of Internal Hazards

Calculations indicate that fission products from detonation of thousands of megatons of yield would have to be in the stratosphere before delayed fallout would cause an average concentration in humans equal to the recommended maximum values for occupational workers (2). Thousands of megatons are typical of a large-scale nuclear attack such as the one described in the section on fallout patterns, which totaled 2500 megatons.

## MANAGEMENT OF FALLOUT

Only a small portion of the vast amount of available information on fallout appears in this text. Although actual fallout patterns are uncertain, fallout can be managed. The Department of Defense estimates that 90% of the persons estimated to die from the effects of residual nuclear radiation could survive in a shelter with a protection factor of 40 (6, 11). A home with two or more stories and an average basement wall exposure of 2 ft or less provides a protection factor of at least 40 throughout the basement (19). Common sense and reasonable understanding of the characteristics of fallout can make fallout a manageable problem.

### Detection of Fallout by the Physical Senses

Ideally, all radiation detection should be done with instruments. Although the thorough control of radiation requires instruments, the physical senses can evaluate the relative magnitude of the hazard. Much, if not all, of the heavy fallout observed during nuclear weapons testing was visible as individual particles falling and striking objects or as deposits accumulated on the surfaces of various objects (1). Although fallout still occurs after the fallout cloud has thinned and cannot be seen, the most hazardous fallout is associated with visible particles (2).

During tests in the Pacific, the fallout was white because it consisted primarily of calcium oxides and carbonates from the coral islands (1). At the Nevada Test Site, fallout was composed primarily of alluvial soil, so it was usually darker (1). War fallout would probably be composed of a mixture of sharp-edged particles, irregular particles, and round particles with smooth surfaces (1). Their color would depend on the explosion environment, but would probably be brown, gray, or black (1).

In addition to the contamination of Rongelap and the Marshall Islanders during the BRAVO shot in the Castle Series at Bikini Atoll, 23 Japanese fishermen aboard the Fukuryumaru (the Lucky Dragon) were exposed to radioactive fallout produced by the test. The vessel was 190 km from ground zero. Fallout began at about 4 hours after detonation and continued for 4.5 hours. During the most intense ash fall, the fishermen could not keep their eyes and mouths open. Their footprints were clearly visible on the ash-covered decks, and (as with the Marshall Islanders) the ash adhered to the bare areas of their skin. Fallout reconstruction indicated that approximately 4-8 mg/cm<sup>2</sup> (3.7-7.4 g/sq ft) of fallout were deposited on the deck (20). The Defense Civil Preparedness Agency (DCPA) has estimated that for each R/hr at 1 hour, 5 mg of particles would be deposited per square foot of area (5 mg/sq ft =  $5.4 \times 10^{-3}$  mg/cm<sup>2</sup>) (4). This quantity of material would be clearly visible. Similarly, for large dose rates and time periods greater than 1 hour after detonation, the amount of particle accumulation would be greater. For example, for



a 150-rad dose delivered in 1 week or less in an open field with the fallout arriving at 1 hour, the dose rate would have to be 50 R/hr at 1 hour and correspond to 250 mg/sq ft deposited on the ground. For the same 150 rads in 1 week or less and fallout arriving at 4 hours after the detonation, the dose rate would have to correspond to 75 R/hr at 1 hour with a total accumulation of 375 mg/sq ft (4).

Realizing that not all individuals would have instruments and that the most hazardous fallout is detectable by the senses, the DCPA has proposed that guidelines be issued to isolated persons. These guidelines (paraphrased unless directly quoted) would be as follows (4):

If you know there has been a detonation, you will want to protect yourself from fallout by going to a shelter (basement, storm cellar, etc.). Fallout will not arrive immediately; it may take several hours. You will probably have time to protect your stock and equipment and to bring food and water into your shelter. If you do not have a radiation-detecting device, you can detect heavy fallout by:

1. "Seeing fallout particles, fine soil-colored, some fused, bouncing or hitting a solid object, particularly visible on shining surfaces such as the hood or top of a car or truck. A white board or piece of white paper on a flat surface may serve as a visual detecting device."
2. "Seeing a dust cloud or general haze in the sky not associated with a dust storm."
3. "Feeling particles striking the nose or forehead or collecting on the hands and arms or in the eyes or between the teeth." This would result in irritation of the eyes, gritty sensation on the lips and between the teeth and a gritty feeling on the forehead, hands and bare arms.
4. "In the rain, after turning on the windshield wiper of your car seeing fallout particles in raindrops slide downward on the glass and pile up at the edge of the wiper stroke, like dust or snow. The particles generally move readily like sand, rather than tending to smear and stick to the glass like fine dust."

If fallout is detected, shelter should be sought immediately. Even if fallout is only suspected and not detected, shelter should be sought. If caught in fallout, the head should be covered with a hat, a piece of cloth, or a newspaper. All outer clothing should be buttoned or zipped. Clothing should be adjusted to cover as much skin as possible. Clothing should be brushed frequently.

In the field, unless otherwise required, use of a shelter should be automatic whenever a small-yield (tactical) burst has been observed, because this type of burst is very likely to produce early fallout (5). Shelter should be used until monitoring or passage of time proves that no fallout exists (5).

#### Evaluation of Hazards

If a nuclear detonation (especially a large-scale exchange) occurs, people will be exposed to fallout. How much they will be affected depends on the magnitude of the exposure and the length of time over which it is delivered. The goal of fallout management is to reduce the magnitude of exposure as much as possible.

No computation of dose or dose rates in the fallout field should be made until the fallout is complete (6). Fallout is complete when the dose rates begin to decrease. If dose rates are increasing, the fallout is still accumulating. In addition, a calculation is not a substitute for accurate instrument readings. A reading taken at waist height will estimate the average whole-body dose a person would receive (5, 13). If personnel dosimetry is available, it must be used. Any calculations made should be conservative.

Except in areas of complete devastation, dose rates greater than 5000 R/hr at 1 hour are highly unlikely (2). After a surface burst, fallout shelters would be needed for a maximum of about 2 weeks (1). Three days is the maximum expected time that military operations will be hampered (14). After 2 weeks, some localized areas may still pose a serious hazard, but the fallout dose rates will be reduced to about  $1 \times 10^{-3}$  the levels present at  $H + 1$  hour (2). After 3 months, the dose rates will fall to  $1 \times 10^{-4}$  of the value at 1 hour; so at 3 months, almost any area can be entered for dose measurements (2). Before entering a contaminated area, an estimated dose rate based on decay curves should be made to evaluate the extent of the hazard. Immediately upon entering the area, an instrument survey should be made to verify the estimates.

In evaluating radiological hazards in a fallout field, one must consider the basis for dose limits. Peacetime dose limits are established to reduce the potential of any long-term effects such as leukemia, cancer, or any general shortening of the lifespan (21). Present limits are 5 rems per year, not to exceed 1.25 rem per quarter. With a documented exposure history, the limit can be raised to 3 rems per

quarter, not to exceed  $5(N - 18)$  rems (where  $N$  is the individual's age) (22). In wartime, the long-term effects of radiation do not influence the wartime performance and potential of individuals. Consequently, the acute effects are used to establish dose criteria. Although all planning for radiological defense will try to keep exposures as low as possible, the question of permissible doses is a command decision based on operational requirements.

Operational exposure is a command decision based on overall staff advice. It will vary from situation to situation and most often would be influenced by the mission. Table 10 presents the NATO Operational Exposure Guide (5, 14). As seen, the acceptable exposures during wartime are much higher than during peacetime. In addition, the acceptable dose at given time depends on the exposure history of each person.

Table 10. NATO Operational Exposure Guide

Radiation status 2,5	Total past cumulative dose 4	Single exposure criteria 1,3	
RS-1 Units	<75 rad	Negligible Risk	$\leq 5$ rad
		Moderate Risk	$>5 \text{ rad} \leq 20 \text{ rad}$
		Emergency Risk	$>20 \text{ rad} \leq 50 \text{ rad}$
RS-2 Units	75-150 rad	All further exposure considered Moderate or Emergency Risk.	
		Moderate Risk	$\leq 5$ rad
		Emergency Risk	$>5 \text{ rad} \leq 20 \text{ rad}$
RS-3 Units	>150 rad (Threshold for onset of combat ineffectiveness)	All further exposure considered Emergency Risk.	
		Emergency Risk	$<5$ rad

<sup>1</sup> For operations in radiologically contaminated areas, the operation exposure guide established by the commander can be any number in the risk range appropriate to the unit's mission and radiation status.

<sup>2</sup> Radiation status categories are based on previous exposure to radiation.

<sup>3</sup> Risk levels are graduated within each status category in order to provide more stringent criteria as the total radiation dose accumulated becomes more serious.

<sup>4</sup> All exposures to radiation are considered to be total body and simply additive. No allowance is made for body recovery from radiation injury.

<sup>5</sup> Reclassification of units from a more serious radiation status category to a less serious one is done by the commander upon advice of the surgeon after ample observation of actual state of health of the exposed personnel has been made.

Table 11 identifies the dose rates and stay times for entry into a fallout field with different dose criteria. (Dose rates, doses, and stay time were computed from information in reference 2.) For example, if a dose limit of 150 rads is set, one can enter a 167-rad/hr fallout field (assuming fallout deposition is complete) at 30 minutes after detonation and stay for 4 hours. If the person has to remain exposed for 2 days, unprotected, then at 30 minutes after detonation the highest fallout field he should enter is 100 rads/hr (at  $H + 0.5$ ). Similarly, if only 50 rads is an acceptable dose, radiation fields of only 56 rads/hr and 53 rads/hr, respectively, should be entered. As can be seen, the lower the limits of acceptable exposure, the higher the constraints on operations. It should also be noted that individuals would be able to go into areas of reasonably large dose rates for lengthy periods and still have an acceptable risk (i.e., 50 rads) for a wartime situation.

Table 11. Dose Rates (Rads Hr) at Entry to a Fallout Field for Given Stay Times

Time of Entry Into a Fallout Field After Detonation	Stay Time		
	4 hours	2 days	2 months
<u>Acceptable Dose: 150 Rads</u>			
6 min	375	250	200
30 min	167	100	75
1 hr	107	62.5	40
4 hr	52	16.7	10
10 hr	43	10.0	04.7
24 hr	37.5	05.8	02.2
72 hr	37.5	04.2	00*
<u>Acceptable Dose: 50 Rads</u>			
6 min	125	83	67
30 min	56	33	25
1 hr	36	20.8	13
4 hr	17	05.5	03.3
10 hr	14.3	03.3	01.6
24 hr	12.5	01.9	00.7
72 hr	12.5	01.4	00*
<u>Acceptable Dose: 3 Rads</u>			
6 min	07.5	05	04
30 min	03.3	02	01.5
1 hr	02.1	01.3	00.8
4 hr	01.0	00.3	00.2
10 hr	00.86	00.2	00.09
24 hr	00.75	00.12	00.04
72 hr	00.75	00.08	00*

\* Information unavailable for computation

If the exposure is spread over time, the body can repair some of the radiation damage and thus increase the total acceptable dose. Table 12 (23) illustrates the estimated medical effects of radiation doses delivered over periods of time and the corresponding probabilities of sickness and death. Acceptable doses not resulting in acute radiation casualties are indicated above the heavy black line in the body of the Table.

Table 12. Estimated Medical Effects of Radiation Doses Deposited Over Time

Measured dose (rad)	Early effects for periods of time over which total dose is received										Significant late effect
	1 Day		3 Days		1 Week		1 Month		3 Mo or more		
	Sick-ness	Death	Sick-ness	Death	Sick-ness	Death	Sick-ness	Death	Sick-ness	Death	
0 to 75	0%	0%	0	0	0	0	0	0	0	0	None
100	2%	0%	0	0	0	0	0	0	0	0	None
125	15%	0%	2%	0%	0	0	0	0	0	0	None
150	25%	0%	10%	0%	2%	0%	0	0	0	0	None
200	50%	0%	25%	0%	15%	0%	2%	0%	0%	0%	Some
300	100%	20%	60%	5%	40%	0%	15%	0%	0%	0%	Some
450	100%	50%	100%	25%	90%	15%	50%	0%	5%	0%	Some
650	100%	95%	100%	90%	100%	40%	80%	10%	10%	0%	Some

This table applies to healthy, young adults under usual working conditions. The probability of fatalities will be decreased with adequate medical treatment. The casualty estimates are based on an interpretation of the best current available evidence, and may be changed as more information is accumulated.

This table is for planning purposes only, and is not designed for tactical use.

Table 13 expresses the 0% sickness and 0% death doses as an average daily and hourly rate. These doses will be very important in the postnuclear environment when individuals have to work in areas of relatively low levels of radiation.

Table 13. Daily and Hourly Average Dose Rates for Estimated 0% Sickness and 0% Mortality

Time	0% Sickness			0% Mortality		
	Total Dose	Daily Rate	Hourly Rate	Total Dose	Daily Rate	Hourly Rate
1 day	75	75	3.1	200	200	8.3
3 days	100	33	1.4	200	067	2.8
1 week	125	17.8	0.74	300	042.9	1.8
1 month	150	05	0.21	450	015	0.63
3 months	300	03.3	0.14	650	007.2	0.30

Although no calculation of dose rates and stay times are made in this paper, the interested reader can find several different methods (all producing the same results) in various publications (2, 5, 14).

### Fallout Shelters

A loose definition of a fallout shelter is any structure that offers a protection factor reasonably greater than 1. Ideally, the best shelter would be a shelter constructed before an attack, like a home shelter (Figure 49) (6) or a public shelter.

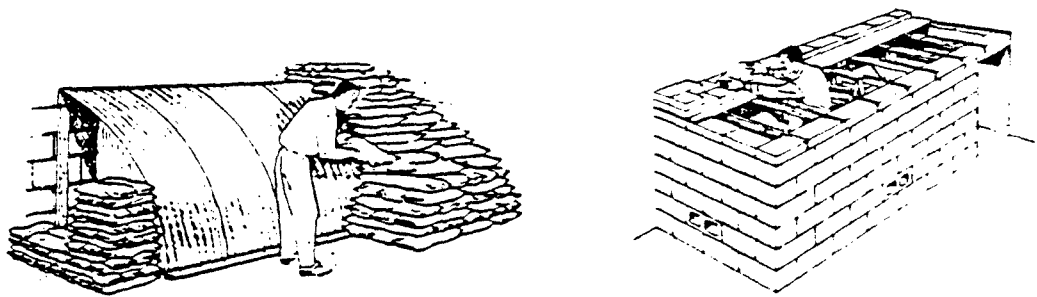


Figure 49. Home fallout shelters constructed before attack

What is a good protection factor for a shelter? Since gamma radiation attenuates exponentially, the highest protection factor achievable is best. For example, if a protection factor of 100 is good, and reduces the dose to 50 rads, then a protection factor of 1000 is better, since it reduces the dose to 5 rads. Federal Civil Defense guidelines set a national goal for a minimum protection factor of 40 for public shelters not originally designed as a shelter (11, 19). A protection factor of 40 will reduce dose rate levels by 97.5%. The minimum protection factor for a designed shelter is 100 (11). For personnel in military operations, the military operational requirements and the local fallout levels will determine the fallout protection factor that is needed.

In addition to the protection factor offered by a potential shelter, several other elements should be evaluated. Although a potential shelter may provide excellent radiation shielding, its value as a shelter can be limited. In addition to adequate shielding, shelter requirements should include the following: good ventilation, adequate sanitation, adequate space for the number of people, and room to store food and water (16). Actual requirements for a particular fallout shelter are determined by the location and the mission.

Army planners expect 3 days to be the maximum time for continuous occupation of a field-expedient shelter (14). In such cases, comfort can be sacrificed for safety. The standard shelter space recommended in the National Fallout Shelter Survey is 10 square feet of floor space per person and at least 65 cubic feet of air space per person (11). The following gives examples of field-expedient shelters and information on the use of existing structures as fallout shelters.

#### Field-Expedient Shelter

Figure 50a illustrates a typical foxhole. It provides a transmission factor of about 0.1 (protection factor of 10) and is rather simple to construct. Figure 50b illustrates the typical foxhole modified by a covering of earth. In this case, the increased protection results in a transmission factor of 0.01. This covering of earth reduces the "sky shine," or radiation that has scattered back down to the ground from the air.

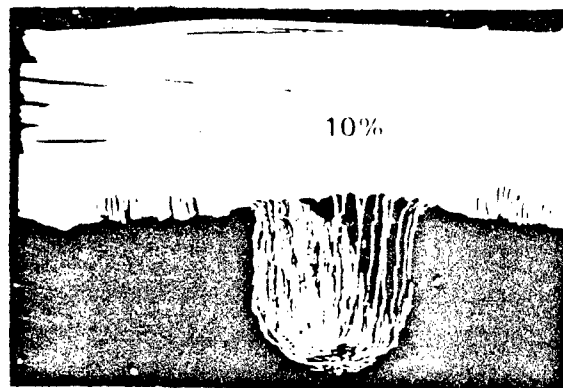


Figure 50a. Typical foxhole, with protection factor of 10

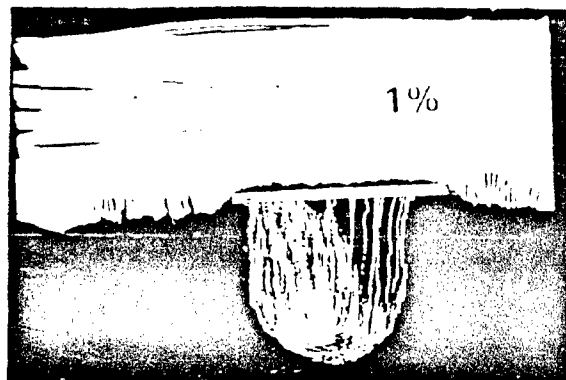


Figure 50b. Typical foxhole modified with protection factor of 100

The dozer trench in Figure 50c is essentially an expanded foxhole, but it is not quite as effective as a conventional foxhole (a transmission factor of only 0.2-0.3). The advantages of a dozer trench are that it requires a minimum of engineering effort, and only about 2 feet of trench length is required to shelter each person. In addition, the dozer trench is excellent for protecting a large number of bedridden casualties. The protection and the comfort of this shelter can be improved as time passes by digging the trench deeper, undercutting the walls, erecting tents over some parts of the trench, and providing flooring. Thought should be given to water drainage, especially if rain is expected with the fallout or after fallout deposit. It is estimated that one dozer and its operator could cut 600 feet of trench in 100-ft lengths within 5 hours (14).

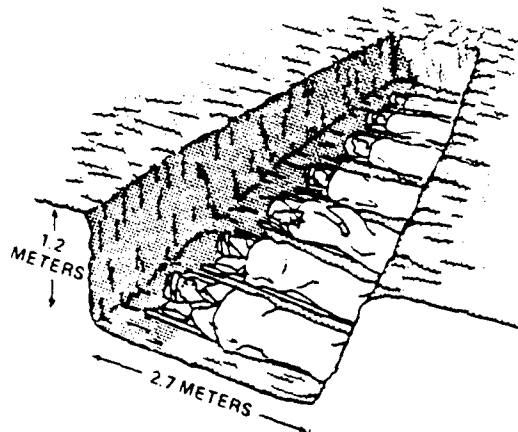


Figure 50c. Dozer trench

Figure 50d (14) shows a sandbag wall that can be built around hospital tents or lightly constructed buildings. Sandbags 4 feet high give a transmission factor of 0.2-0.4. Unfortunately, the effort required to achieve this protection makes such measures only marginally feasible. Sandbagging is more effective for supplementing and reinforcing other methods. If an existing structure needs protection, mounding the dirt with a dozer takes much less time.



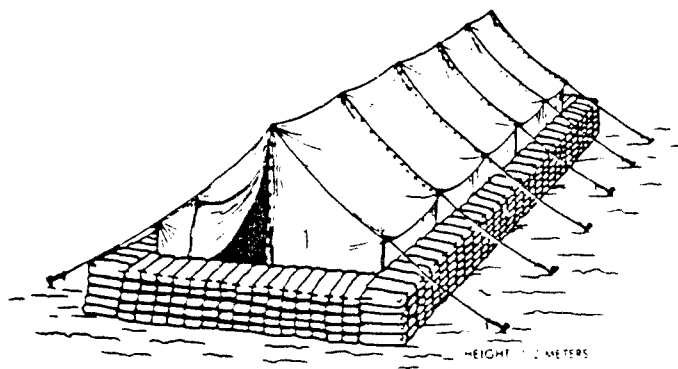


Figure 50d. Sandbagged tent

Figure 50e (14) illustrates an efficient, expedient shelter that combines the use of vehicles and dirt. It is sometimes called the "wagon master concept." For this shelter, a trench 6 inches deep and the width of a vehicle is dug around an erected tent. The dirt is piled carefully on the outside of the trench. An additional trench is dug to lower the wheels on one side of each vehicle, so that the vehicles will sit at an angle. This increases their effectiveness as shielding because the radiation would have to penetrate the beds of the vehicles. If the fallout were collected and removed from inside the compound, a transmission factor of 0.8 would be seen. This structure requires about 2 hours to build, and it can be occupied or evacuated in a matter of minutes.

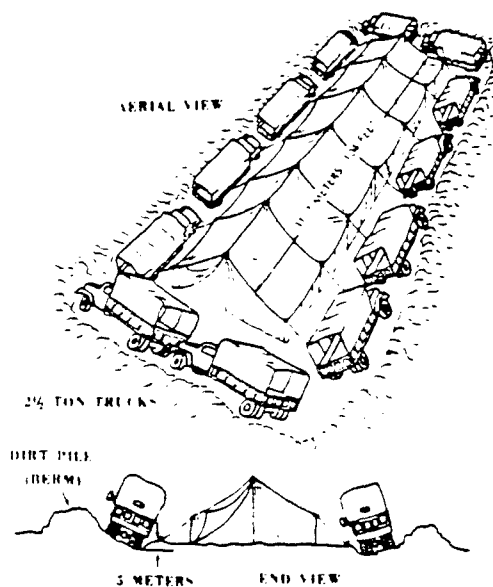


Figure 50e. Wagon master concept

### Using Existing Structures as Fallout Shelters

The former Defense Civil Preparedness Agency (DCPA) evaluated many existing structures for their ability to provide shelter from fallout. In the following discussion, the lower protection factor relates to locations near entrances, windows, and the outer portion of aboveground floors; the higher number pertains to locations remote from the openings and in central areas. [ Figures 51 (14) and 52 (19) illustrate the descriptions. ]

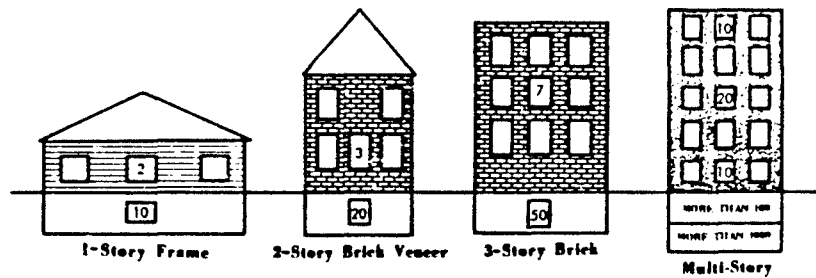


Figure 51. Approximate protection factors for existing structures

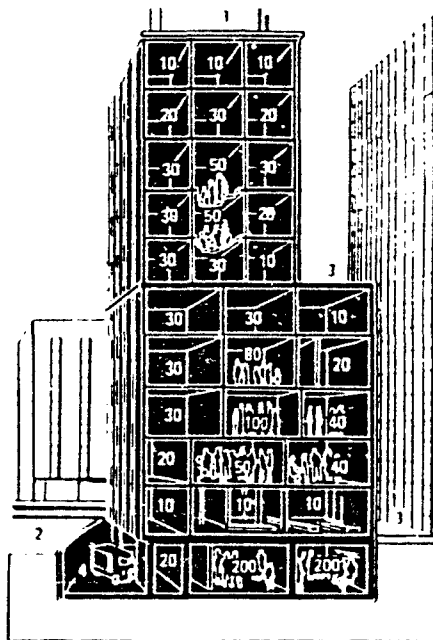


Figure 52. Protection factors for various locations in a large building

Subway stations, tunnels, mines, and caves with a larger volume relative to entrances have a protection factor (PF) of 1,000-10,000 (19). Basements and subbasements of massive (monument) masonry buildings provide a protection factor of 100-1000 (19). Basements and subbasements of large, fully engineered structures having any floor system over the basement other than wood, concrete flat plate, or band beam supports, will provide a PF of 100-1000 (19). Basements or subbasements of buildings with flat plate or a banded beam floor system provide a PF of 100-200 (19). Protection factors for the basements of good frame and brick veneer structures, including residences, are about 10-50 (19). The first three stories of buildings with "strong" walls, fewer than ten aboveground stories, and less than 50% openings will provide protection factors of 20-80 (19). The fourth through ninth stories of buildings with "strong" walls, fewer than 10 aboveground stories, and less than 50% openings have a PF of 20-100 (19). A protection factor of about 20-80 is provided by the first three stories of buildings with "strong" walls, fewer than ten aboveground stories, and more than 50% openings; the same is true for the first three stories of buildings with "weak" walls and less than ten aboveground stories (19). The fourth through ninth stories of buildings with "weak" walls and also all aboveground stories of buildings with ten or more stories have values of 20-100 (19). And finally, in general, in all aboveground locations, the top floor has the lowest protection factor because of fallout on the roof.

In the examples above, the protection factor was calculated for buildings, assuming that fallout is deposited uniformly on the ground and on roof surfaces. The shielding effects of nearby buildings were taken into account, but the movement of fallout by wind and rain was not. The effects of building damage by blast were also not considered. Because these effects can vary greatly, radiation measurements should be made in any shelter being considered for use. In that way, the occupants can select those areas of the lowest dose rates.

It is important to note that the middle floors of tall buildings offer good fallout protection mainly because they are remote from the fallout both on the ground and on the roof (Figure 52) (19). However, these middle areas do not offer good protection against blast and initial nuclear radiation. But in localities not affected by the direct effects of a nuclear detonation, the fallout protection offered by the middle areas of large buildings can be a valuable resource.

When discussing field-expedient shelters or the use of existing structures as shelters, it is interesting to note how local terrain may increase the protection factor. Figure 53 addresses the effects of prominent terrain features, such as hills and valleys, on the protection factor (19). The upper sketch illustrates the protection afforded a person standing on the top of a small, steep hill that falls off in all directions and in a small, steep depression. The calculation is based on a 100-ft-diameter hemisphere. The protection factor of

the hill increases to 1.8 because the hill hides much of the fallout beyond the immediate area. A small, deep depression does not offer much improvement because fallout lies on the side of the depression.

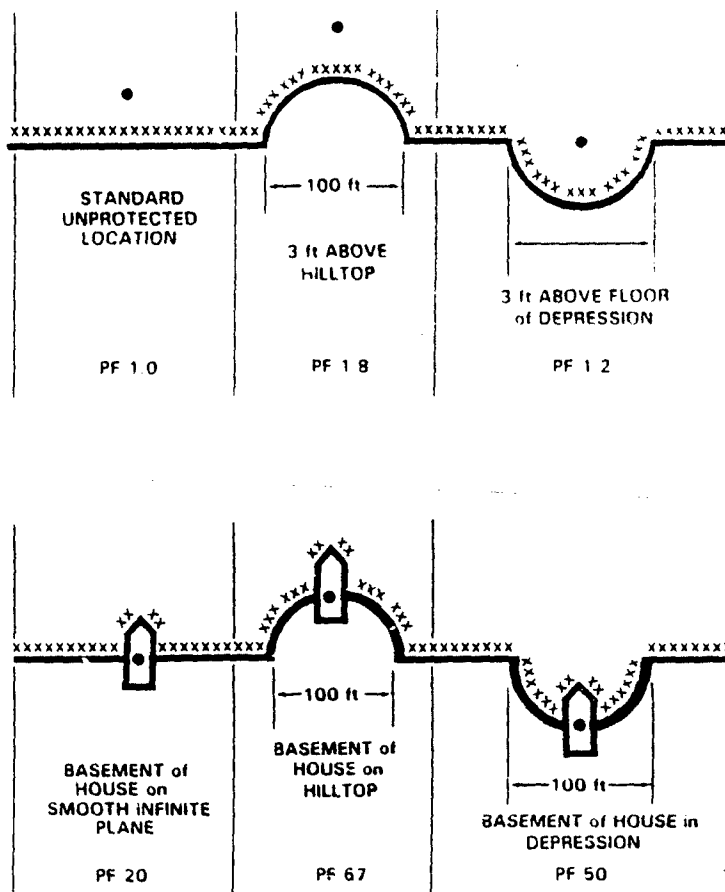


Figure 53. Effects of terrain features on protection factors

The lower sketch illustrates the effect of the same hill and depression on a basement shelter. This terrain has a greater effect on the protection offered by the basement. It is a home basement on a smooth, infinite plane with a protection of 20. This same house built on the top of the hill would have a protection factor of 67. If built on the floor of a small, steep depression, its protection factor would be 50. Unfortunately, the use of such terrain features must be determined by the actual situation. Although a small, steep depression may add to the protection factor, it could also act as a fallout collector depending on the drainage conditions during rain-fall. Similarly, the use of a house and basement on a hill may not be wise if enemy contact is possible.

Although a field-expedient shelter or an existing shelter can be used, some thought should be given to area management if fallout levels permit. In extreme cases, it may be necessary to go outdoors for sanitation purposes and/or exercise. Since 50% of the doses would occur in an area of 10 meters in radius, a 10-meter area could be cleared by pushing away or washing away the contamination. In addition, some of the fallout could be buried and/or a mound could be made on the perimeter of the "cleared" area. Such an area would add flexibility to the shelter operations (for exercise, sanitation, etc.) and would act as a staging area for postattack recovery.

Decontamination and area management should not be used as substitutes for adequate shelters (1). In the early fallout environment, they should only complement the shelter; they should not be considered as countermeasures to be applied in the early fallout period (1). Decontamination is actually a postattack recovery method (1). It should be used to allow personnel to leave the shelter earlier for survival resources such as food and water, or for completion of an assigned mission.

#### Shelter Entrance

To adequately control fallout, some thought must be given to the method of entering a shelter. Before entering, one must remember that fallout is like sand, and the decontamination of fallout is like cleaning sand off one's body after being "buried" on the beach, or cleaning sand out of a beach cottage after a beach party. The size of the fallout particles should allow them to fall off clothing. To remove the contamination, the shoes should be brushed and the clothing should be shook, brushed, or vacuumed. This procedure is better performed outside the fallout shelter (under cover). All outer clothing should be removed and stored in an isolated area. If the fallout is embedded, the clothing should be discarded or eventually washed or held in storage until the fallout has physically decayed. Contaminated portions of the skin and hair should be washed or brushed, taking care not to injure the skin. Normal procedures of personal cleanliness are sufficient for personnel decontamination in a nuclear attack.

After entering the shelter, all doors, windows, and nonvital vents should remain closed while the fallout is occurring. Radiation levels inside the shelter should be checked to find the lowest levels. One should not assume that a shelter, especially a nondesigned shelter, has equal protection in all areas. For example, inside a normal home basement (unmodified for fallout protection), the center of the basement offers the least protection, whereas the greatest protection is in the corners and along the walls. The interior of the shelter should be checked for any contamination that has been brought in. If there is contamination, it can be cleaned by vacuuming, brushing, wiping, scrubbing, etc. One should remember that fallout is like sand and that it will get into all the cracks and crevices in the floor.

### Decontamination of Patients

In a disaster such as a nuclear detonation, there will be casualties, even if they are only those persons injured in rushing to a fallout shelter. In general, the radiological hazards to a contaminated patient and the attending medical personnel will be small. Medical or surgical treatment needed when a life is in danger should not be delayed because of possible contamination. A checkpoint should be established immediately after receiving a contaminated patient, and the patient should be surveyed for contamination. Ideally this checkpoint is located outside the treatment facility. If contamination does exist, removal of the outer clothing and shoes, in most instances, will remove 90%-95% of it. Washing the exposed areas of skin increases the removal of contamination to 99%. If the hair cannot be decontaminated, it should be clipped closely. The skin should not be shaved since, depending on the type of contamination, its absorption may be enhanced. If a large number of patients are being stripped because of contamination, the attending personnel should be checked frequently or else they should change their clothes periodically, because it is inevitable that they will also become contaminated. Care should be taken not to contaminate survey instruments because they will then produce positive readings on patients who are not contaminated. No special soap, detergent, or acids are needed to remove fallout particles (1).

Skin can be decontaminated by washing with mild soap and water or detergent and water for 2-3 minutes. If necessary, a soft brush with heavy lather and tepid water can be used, but care must be taken not to scratch or erode the skin. Each subsequent cleaning (if needed) should be checked for effectiveness by monitoring with a radiation detector. Cuts or breaks in the skin should be flushed with large volumes of running water as soon as possible. Wounds may be spread open to permit flushing. Mechanical cleaning or microsurgery can then be used to remove any remaining contamination. After each step, the wound should be checked until decontamination is complete.

Except in rare cases, external radioactive contamination of personnel is not a medical emergency; i.e., the life of a person does not depend on emergency procedures against the contamination within minutes or hours. While all reasonable measures must be taken to prevent the spread of contamination, the treatment for emergencies such as trauma, shock, and hemorrhage always takes precedence over decontamination. No patient should be denied therapy or medical attention because of contamination. It is important that necessary therapy not be hindered by monitoring of the patient for contamination.

In a mass-casualty situation such as could occur in a fallout field, it would not be possible to devote extensive periods of time to a few decontaminations. As stated above, the removal of contaminated clothing and the washing or wiping of exposed areas of the body are adequate. Although some contamination may remain, the risk incurred to the patient and attending medical personnel is negligible compared to the overall hazards and/or the inefficient use of medical personnel when a large number of casualties are present. After the emergency has subsided, any contamination remaining on the patients can be removed by the methods already described.

#### Postattack Food Sources

A fully stocked fallout shelter should contain enough food and water for 2 weeks. This includes about 7 gallons of water per person (6). Any sealed sources of food and water are acceptable, although sources already inside the shelter are preferred. Gamma radiation from fallout does not damage food. Contamination is normally confined to the outer surface of sealed containers, so it is necessary only to wash the container before opening it. Unsealed food sources must be suspected of contamination, and must be isolated until checked. Since only the outside of unsealed food becomes contaminated, the food can be made safe for eating by washing, peeling, or otherwise removing contaminated parts.

Depending on the location, many emergency sources of water may be available, such as hot water tanks, flush toilets, ice cube tray, or bottled water. If water is exposed, it must be considered contaminated. Specialized and normal water treatment can be used. Several 2-inch layers of sand, gravel, humus, coarse vegetation, and clay can be used as a filter to remove 90% of the dissolved radioactive materials (6). A 6-inch column of loose dirt gives reasonable results. In any case, the filtered water should be boiled or treated with iodine purification tablets or calcium hypochlorite to kill any biological contaminants.

Since the risk of internal contamination is relatively minor for short periods of time, no one should remain thirsty or hungry for fear of contaminated sources (1, 9, 12). If it is necessary to eat contaminated food because noncontaminated food is not available, the least contaminated food should be eaten first. In terms of the overall impact of a nuclear attack, the problems of protecting food and water from radiation contamination in the early postattack period are probably minor, compared to the problem of protecting them from bacterial contamination (1). Bacterial contamination could result from the disruption of essential services such as gas and electricity, which are needed to preserve food.

In a postattack recovery, food sources growing in fields would be contaminated. Young plants can incorporate radionuclides from the soil, so they should be evaluated. Mature plants near harvest would probably not incorporate any significant amounts of radionuclides. If foodstuffs must be grown in contaminated soil, liming can be used to increase the concentration of calcium and thus decrease the uptake of strontium. In addition, in highly contaminated fields, food low in calcium requirements could be planted (e.g., potatoes, cereals, apples, tomatoes, peppers, sweet corn, squash, and cucumbers) (6). Foods requiring a high intake of calcium could then be planted in the areas of least contamination. Examples of foods with high calcium intake are lettuce, cabbage, kale, broccoli, spinach, celery, and collards (6).

### Postattack Recovery

The three principal ways of reducing exposure of people in a contaminated area are to (a) shield against radiation by remaining in shelter, (b) evacuate from the area, and (c) decontaminate. However, any kind of practical countermeasure may be used. The effectiveness of the exposure control is determined by the number of casualties it prevents (1).

Time spent outside a shelter should be kept to a minimum when the dose rates are high. In addition, as much protective clothing as practical should be worn. For example, boots should be worn and the cuffs of pants should be tied. Areas of high contamination, such as puddles or dust, should be avoided as much as possible. If winds sweep contaminated surfaces that are relatively smooth, they can quickly redistribute the fallout against curbs, buildings, or other obstructions, thus causing areas of high contamination. Puddles usually indicate areas of localized concentration caused by runoff. Disturbing a dusty area can cause resuspension of contaminated particles in the air, so a handkerchief or some other covering for the nose and mouth should be used. Unnecessary contact with contaminated surfaces should be avoided. Personnel dosimetry must be worn if available.

During postattack recovery, some areas may have higher dose rates than desired. In these areas it will be possible to leave the shelter, but in order to keep personnel exposures down, the shelter must function as a base camp. The recommended times for remaining in it are based on the radiation levels and the acceptable risks (doses).

In general, personnel in a fallout area should not leave a shelter during the first day or so after fallout arrives because radiation levels are high. If a shelter provides an appreciable amount of protection, it is generally better to remain in it and improve it rather than attempt to evacuate to an uncontaminated area. There are two important reasons for this: (a) personnel might receive excessive exposures while moving out of the area, and (b) some time might be needed to identify the location of safer areas and to check whether



or not any habitable space is available in those areas. If evacuation on foot is attempted because no vehicles are available, some consideration should be given to using closely packed formation. A group of 20 persons can achieve an average dose reduction of 2 below that received if they move separately. The average dose reduction for a group of 60 persons could be a factor of 3 (1).

Fallout behaves physically like any other dirt or moisture. The particles are usually finely divided, so they adhere closely to other materials and tend to settle in pores and crevices. Selection of the type of decontamination to be used depends on factors such as availability, type of apparatus, type of surface to be decontaminated, and how the contamination is held to the surface to be decontaminated. On contaminated objects, the radioactive material is usually in close contact with dirt, oil, or other substances on the surface. Decontamination of fallout is usually a physical process, not a chemical one. Acids, detergents, or elaborate surgical scrubbing techniques should not be required. The three general methods of radiological decontamination are aging, sealing, and removal.

In time, aging reduces contamination to a negligible amount. The time required depends on the rate of decay and the amount of radioactive contaminant present. Objects to be decontaminated by aging should be marked in some fashion and set aside or bypassed until the radioactivity is no longer hazardous.

Sealing is the process of covering or fixing a radioactive contaminant with some type of material that acts as a shield to prevent the escape of the nuclear radiation. In certain cases, as with high-energy gamma radiation, fixing may be used not to offer shielding but to prevent the radiation's subsequent spread. The feasibility of fixing as a method of decontamination is very highly dependent on the situation.

Although aging is the most effective means of decontamination, most decontamination is done by removal. It is necessary to choose a method of removal that cleans away the substance holding the radioactivity. Three principles involved in removal operations are:

Radioactive contamination is not neutralized or destroyed but only removed to a less hazardous area, consideration must be given to disposal of the removed radioactive contaminant.

The type of contaminated surface dictates the selection of the decontamination procedures. Fallout particles can penetrate porous or rough surfaces such as concrete, unglazed bricks, unpainted wood, asphalt, and weathered or corroded surfaces. On the other hand, well painted and smooth, clean metal surfaces are nonporous, so they are not susceptible to contamination.

To save time and labor, decontamination steps should proceed from the easier to the more difficult. First, large amounts of contaminant should be removed by such methods as brushing or pressure flushing. The surface should then be checked and the remaining contaminant removed by more thorough methods as necessary. Table 14 gives the efficiencies of some typical means of decontamination.

Table 14. Typical Decontamination Efficiencies (Percent)

Material	Vacuum	High- Pressure Water	Sandblasting	Steam Cleaning
Glass	98	98	100	97
Painted wood	99	98	100	91
Asphalt	72	92	92	22
Concrete	74	98	100	21
Unpainted wood	36	85	99	85

## REFERENCES

1. Green, J. C. Fallout Radiation Exposure Control (An Introduction). Post-Attack Research Division, Office of Civil Defense, 1965.
2. Glasston, S. and Dolan, P. J. The Effects of Nuclear Weapons. Department of Defense and Department of Energy, 1977, Washington, DC.
3. Day III, C. E. Nuclear Weapon Fallout. The Medical Effects of Nuclear Weapons. Armed Forces Radiobiology Research Institute, Bethesda, MD, May 1981.
4. Response to DCPA Questions on Fallout. Prepared by the Subcommittee on Fallout Advisory Committee on Civil Defense, National Academy of Sciences, with notes and comments by Jack C. Green. DCPA Research Report 20, Defense Civil Preparedness Agency, November 1973.
5. Operational Aspects of Radiological Defense. FM 3-12 (FM 11-5). Departments of the Army and Navy, August 1968.
6. Radiological Defense Textbook. SM-11.22-2. Office of Civil Defense, Department of Defense, June 1968.
- \*7. Statement of United States Naval Radiological Defense Laboratory on Prediction of Fallout.
- \*8. Kellogg, W. W. Atmospheric Transport and Close-In Fallout of Radioactive Debris From Atomic Explosions.
- \*9. Sanders, J. B., Placak, O. R., and Carter, M. W. Report of Off-site Radiological Safety Activities - Operation Tea Pot, Nevada Test Site, Spring 1955.
10. Fallout Prediction. FM 3-22. Department of the Army, October 1973.
11. Fallout Shelters. TR-39. Office of Civil Defense, December 1967.
- \*12. Dunning, G. M. Radiation From Fallout and Their Effects.

---

\*The Nature of Radioactive Fallout and Its Effect on Man. Hearings Before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy Congress of the Congress of the United States. Eighty-fifth Congress, May 27-29 and June 3, 1957.

13. Shelter Design and Analysis, Vol. I, Fallout Prediction. TR-20- (Vol I). Office of Civil Defense, Department of Defense, May 1964.
14. Nuclear Handbook for Medical Service Personnel. TM 8-215. Department of the Army, April 1969.
15. Report of Committee IV on Evaluation of Radiation Doses to Body Tissues From Internal Contamination Due to Occupational Exposure. ICRP Publication 10. Pergamon Press, 1968.
16. Limits for Intakes of Radionuclides by Workers. ICRP Publication 30. Report Committee II, International Commission of Radiation Protection. Pergamon Press, 1978.
17. Report of the Task Group on Reference Man. ICRP Publication 23. Pergamon Press, 1975.
18. Management of Person Accidentally Contaminated With Radionuclides. Report No. 65. National Council on Radiation Protection and Measurements. Washington, DC 20014, 1980.
19. DCPA Attack Environment Manual. Defense Civil Preparedness Agency, Department of Defense, June 1973.
20. Hubner, K. F. and Fry, S. A. The Medical Basis for Radiation Accident Preparedness. Proceedings of the REAC/TS International Conference, Elsevier/North-Holland Inc., New York, 1980.
21. Instructions Concerning Risks From Occupational Radiation Exposure. Regulatory Guide 8.29. U.S. Nuclear Regulatory Commission, Washington, DC, July 1981.
22. Code of Federal Regulations, Title 10, Part 20. U.S. Government Printing Office, Washington, DC 20402, 1981.
23. Radiological and Disaster Recovery at Fixed Military Installations. TM 5-225. Department of the Army, June 1966.
24. Shleien, Bernard. External radiation exposure to the offsite population from nuclear tests at the Nevada Test Site between 1951 and 1970. Health Physics 41: (2), 1981.